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CONTENTS.

PROCEEDINGS.

PART II.

TECHNICAL PAPERS.

Ferrous Metals.

	Page
Molybdenum as an Alloying Element in Structural Steels—G. W. Sargent	5
Discussion	29
A Note on Stresses Caused by Cold-Rolling—H. M. Howe and E. C. Groesbeck	31
Discussion	38
On the Shattered Zones in Certain Steel Rails, with Notes on the Interior Origin of Transverse Fissures—J. E. Howard	44
Discussion	60
Effect of Machining and of Cross-Section on the Tensile Properties of Malleable Cast Iron—H. A. Schwartz	70
Chain Cable and Some of its Physical Properties—C. G. Lutts	80
Discussion	102

Non-Ferrous Metals.

A Note on the Constitution of Certain Tin-Bearing Brasses—William Campbell	104
Fatigue and Impact Fatigue Tests of Aluminum Alloys—W. A. Gibson	115
Discussion	133

Cement, Concrete and Ceramics.

The Volume-Moisture Relation in Sand and a Method of Determining Surface Area Based Thereon—R. B. Young and W. D. Walcott	137
Effect of Hydrated Lime and Other Powdered Admixtures in Concrete—D. A. Abrams	149
Discussion	204
Effect of Rodding Concrete—F. E. Giesecke	219
Discussion	231
Some Determinations of the Stress-Deformation Relations for Concretes under Repeated and Continuous Loadings—G. M. Williams	233
Discussion	250

Road Materials, Timber and Rubber.

PAGE

Impact Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways—H. S. Mattimore 266
Discussion 277
The Standard Deval Abrasion Test for Rock—F. H. Jackson 278
Discussion 291
Some Relations between the Characteristics of Steam-Distilled Petroleum Residuals—B. A. Anderton 298
Discussion 312
The So-Called Asphalt Content of Road Oils—B. A. Anderton and D. G. Taylor 314
Discussion 320

Miscellaneous Materials.

The Uses and Properties of Water-resistant Plywood—A. Elmendorf 324
Construction of Steam Hose—J. M. Bierer 355
Discussion 359

Testing Apparatus and Methods of Testing.

Improved Elastic Limit Recorder—C. H. Marshall 361
A High-Speed Alternating Torsion Testing Machine—D. J. McAdam 366
Discussion 371
An Apparatus for Delicate Flexure Tests and Some Results of Such Tests—W. J. Francke 372
Discussion 387
A New Method for Calibrating Brinell Hardness Testing Machines—J. L. Jones and C. H. Marshall 392
Discussion 396
Ductility Testing Machines—T. Y. Olsen 398
Discussion 404
A New Type of Automatic Cement Tester—T. Y. Olsen 408
A New Method of Testing Galvanized Coatings—Allerton S. Cushman 411
Discussion 422
An Instrument for Measuring the Hiding Power of Paints—R. L. Hallett 426
Discussion 436
A New Colorimeter for White Pigments and Some Results Obtained by Its Use—A. H. Pfund 440
Discussion 449
Further Development of the Plastometer and its Practical Application to Research and Routine Problems—H. Green 451
Discussion 483
Testing of Porosity of Electric Porcelain—W. D. A. Peaslee 495
Subject Index 501
Author Index 507

MOLYBDENUM AS AN ALLOYING ELEMENT IN STRUCTURAL STEELS.

By G. W. Sargent.

Historical.

From the following excerpt which is taken from "Helmet and Body Armor in Modern Warfare," by Bashford Dean of the Metropolitan Museum of Art, New York City, it is evident that even as early as approximately 1330 A. D., molybdenum was used in the manufacture of steel, though perhaps not knowingly.

"As this is written I learn from my friend, Dr. M. Mayajima of Tokyo, this interesting point, which he in turn had from the metallurgist, Dr. O. Kochi of the Faculty of Technology of the Imperial University of Tokyo. It appears that years ago a German steel expert analyzed a part of a sword blade made by the famous Japanese artist, Masamuné (1330±) and he discovered that the rare element molybdenum, doubtless as an impurity, in a certain proportion. This led the discoverer to determine the local source of Masamuné's alloy iron; thereupon he purchased this iron in large lots, much to the surprise of the Japanese who later, when they analyzed captured German cannon, decided where a part at least of the molybdenum ore was obtained."

The early investigators of the effects of the addition of molybdenum to iron or steel, stated such steels were red short: Thus Thomas Blair in 1894,[1] wrote of a case "where 1.0 per cent of molybdenum rendered good iron red short and utterly worthless;" and John A. Mathews[2] reports having found two steels containing 1.87 per cent and 2.99 per cent of molybdenum, respectively, both low in carbon, unforgeable, while a third steel with 0.95 per cent of molybdenum did not develop this red short feature, although it was seamy. Mathews, however, added he did not believe the results obtained were due to the

[1] "Tungsten and Chromium Alloys."
[2] *Journal*, Iron and Steel Inst., 1902.

molybdenum, but more likely to the quality of the alloy used in making the steels. That these results were most likely due to the quality of the alloy used in their manufacture is affirmed by the fact that W. Von Lipin[1] made by the crucible process, two steels at the Puteloff Steel Works, St. Petersburg, Russia, analyzing 0.54 per cent carbon, 3.72 per cent molybdenum and 0.55 per cent carbon, 3.80 per cent tungsten, respectively, and he advises that both steels are generally alike, but that the molybdenum steel seemed tougher and withstood hammering better. Then again, *La Metallurgie*, March, 1896, quotes from experiments at the Creusot Works of Schneider et Cie in France, which showed that 0.20 to 0.30 per cent of molybdenum in 0.20-per-cent to 3.0-per-cent chromium armor-plate steels rendered them harder and less brittle. This was probably the first instance of the use of the chrome-molybdenum combination for the production of tougher steels. Brierly and Ibbotson[2] state that experimenters are by no means unanimous with respect to the influence of molybdenum on the mechanical properties of steel and according to their investigations of the commercial molybdenum alloys available "it would be surprising if they were."

Between 1902 and 1904, a number of molybdenum steels were made at the Creusot Works in France. The *Iron and Steel Magazine* for 1904 gives the heating and cooling curves of the following steels as made by E. Saladin, Metallurgical Engineer of these works:

CARBON, PER CENT.	NICKEL, PER CENT.	CHROMIUM, PER CENT.	MOLYBDENUM, PER CENT.
0.28	....	....	1.83
0.11	....	1.48	1.66
0.89	....	1.48	1.53
0.21	2.83	0.58	0.80

Most of the molybdenum steels produced at the Creusot Works were used by Leon Guillet of the De Dion Bouton Cie for what were the first systematic investigations. In the *Revue de Metallurgie*, 1904, Guillet classifies the carbon-molybdenum steels as follows:

[1] *Engineering*, 1897.
[2] "The Analysis of Steel Works Materials," 1902.

MICROSTRUCTURE.	STEELS UP TO 0.20 PER CENT CARBON.	STEELS UP TO 0.80 PER CENT CARBON.
1st Series—Pearlite.....	0 to 2 per cent Molybdenum	0 to 1 per cent Molybdenum
2d " "—Special constituent	Molybdenum greater than 2 per cent	Molybdenum greater than 1 per cent

Mild steels up to 9.3 per cent molybdenum, and 0.80-per-cent carbon steels up to 14.6 per cent molybdenum were investigated. Guillet remarked upon the great difficulty of mechanically working the high molybdenum alloys, stating that in the first series, steels containing more than 4.5 per cent molybdenum could not be hammered, or more than 2.0 per cent molybdenum in the second series. He points out that from 0.50 per cent molybdenum to 1 per cent molybdenum in the 0.20-per-cent carbon steels, the pearlite structure is more accentuated than is the case with straight carbon steel, and with 2.0 per cent molybdenum the pearlite becomes extremely broken up. In the series up to 0.80 per cent carbon, the pearlite is extremely finely divided and from 1.0 per cent molybdenum up, the special constituent appears in increasing amounts. This special constituent, as in the case of tungsten steels, makes the steels brittle and hard. The tension test values show high ultimate strengths and elastic limits with low elongation and reduction of area. The pearlite steels show a yield point much higher than ordinary steels, but in spite of this, Guillet says "they have high elongation and good twisting strength. They are not more brittle than carbon steels, but are perceptibly harder." In other words, in 1904 Guillet pointed out that the commercial molybdenum steel which is used for structural purposes should not contain more than 1 per cent of molybdenum.

Guillet's paper[1] refers to the nickel molybdenum steels as having high ultimate strengths and elastic limits with medium contractions and also high resistance to shock. In summating, Guillet states the effect of molybdenum in steel is similar to that of tungsten, but one-fourth less quantity is required.

Gustave Gin[2] states that "molybdenum increases largely the ductility and elasticity of hard steels, for 0.25 per cent molybdenum will increase the extension to the point of rupture

[1] *Journal*, Iron and Steel Inst., 1906.
[2] "The Electrometallurgy of Rare Metals," American Electro-chemical Society, 1907.

40 per cent, and the addition of 1 per cent molybdenum to chrome steels of great hardness, permits of their being worked rather easily." He adds that "could ferro-molybdenum be obtained at less cost and in greater quantity, it is certain the consumption of molybdenum would be very much greater."

E. Schaaf-Regelman,[1] express this thought when they write: "Technical difficulties have opposed themselves to the production of pure compounds of molybdenum at low cost, but as soon as a constant supply of the raw material can be assured, these difficulties will be overcome. Molybdenum will then have a wide range of application inasmuch as it is now being used advantageously for improving steel to which it gives increased elongation."

Thomas Swinden[2] investigated four series of molybdenum steels up to 8 per cent content and concludes that the 1 to 2-per-cent molybdenum steels show the most interesting physical properties, and 1 per cent molybdenum gave a most excellent case hardening steel. In making his steels, he recovered 90 per cent of the molybdenum added to the crucible charge and 90 per cent of his ingot weight in finished sound bars. His further study of some molybdenum in alloy steels made in 1913,[3] included steels of the following analysis:

No.	Carbon, per ct.	Manganese, per ct.	Phosphorus, per ct.	Sulfur, per ct.	Silicon, per ct.	Molybdenum, per ct.	Nickel, per ct.	Chromium, per ct.	Vanadium, per ct.
19	0.15	0.22	0.019	0.020	0.058	0.53	0.098	....	....
20	0.19	0.23	0.020	0.023	0.056	0.53	.....	0.95	....
21	0.30	0.33	0.017	0.022	0.067	0.52	.....	....	0.21
22	0.33	0.28	0.021	0.023	0.075	0.96	.....	....	....
23	0.30	0.24	0.018	0.021	0.075	0.45	0.99	....	....
24	0.32	0.28	0.019	0.021	0.082	0.46	.....	0.91	....

Swinden stated: "In the author's previous report several interesting results in mechanical tests were obtained, which gave promise of value as medium tensile steels with good ductility, and a series of mild steels containing molybdenum and other alloys have been prepared and tested." Referring to the tension test values obtained from these steels after heat treating them,

[1] *Engineering Magazine*, Vol. XXXIII, 1907.
[2] *Journal*, Iron and Steel Inst., 1911, Carnegie Scholarship Memoirs, Vol. III.
[3] *Ibid.*, Carnegie Scholarship Memoirs, Vol. V.

he said: "Steel No. 24 gives promise of being a useful steel of cheaper quality than the high tonnage nickel-chrome steels now on the market, which give 110 to 120 tons tensile strength with 12 to 10 per cent elongation. All the steels gave notably high reduction of area figures and in this way resemble nickel and chromium-nickel steels." Under the heading Manufacture, he writes: "The experimental ingots have been made by the crucible process, but it is assured that in making any of the steels commercially, the acid open-hearth process would be used."

Giolitti in 1915 published the following table, giving the effects of various elements on the rate of carbonization, and it is very interesting to note that molybdenum is as effective an aid to carbonizing as tungsten, chromium and manganese:

Proportion of Foreign Material.		Velocity of Penetration in Tenth of Millimeter.
Nickel	2.0 per cent	7
"	5.0 "	5
Manganese	0.5 "	11
"	1.0 "	12
Chromium	1.0 "	10
"	2.0 "	11
Tungsten	0.5 "	9
"	1.0 "	9
"	2.0 "	12
Molybdenum	1.0 "	9
"	2.0 "	11
Titanium	1.0 "	8
"	2.0 "	7
Silicon	0.5 "	6
"	1.0 "	5
"	2.0 "	4
"	5.0 "	0
Aluminum	1.0 "	4
"	2.0 "	2

This review shows that molybdenum, when alloyed with straight carbon steels, chromium, nickel, nickel-chromium and other alloy steels, imparted to them a further increase of strength and toughness, making of them very desirable commercial steels, and this fact has been recognized for years past. Their adoption, however, has been held back on account of the rela-

TABLE I.—TYPICAL RECORD OF MANUFACTURE OF CHROME-MOLYBDENUM STEELS.

HEAT NO. 1180. JANUARY 13TH.

Furnace: 10 – 75 ton 77 B. O. H.

Charge: Clean Scrap . . . . . 99 100 lb. 10.00 A. M.
Cold Pig . . . . . 30 100 "
Hot Metal . . . . . 73 100 " 1.20 per cent Si., 0.032 per cent S.
Spiegel Iron
Nickel Scrap
Nickel

Additions—

Heat Melted:

Carbon
1st Limestone
2d "
3d "
1st Ore . . . . . } 11 000 lb. = 6500 Fe
2d " . . . . . }
3d " . . . . . }
4th " . . . . . }

Nickel
1st Ferro Silicon
2d " "
3d " "
4th " " 10 per cent 11.16 P. M.
Spiegel . . . . . 16 " 1000 lb. 11.22 to 11.25 P. M.
Ferro Chrome . . . . 66 " 3150 " 11.31 to 11.32 P. M.
Ferro Molybdenum 50 " 1504 " 11.42 P. M.
Ferro Manganese . 70 " 1500 " 11.46 P. M.

Heat Tapped: 11.56 P. M. to 12.05 A. M.

Teeming time 32 minutes.

23 – 20×24 Weight 202 700 lb. Yield 93 per cent
217 150 "

Total Metallic Charge:

	Carbon.	Mn.	Sil.	Phos.	Sul.	Ni.	Chr.	Mo.
Analysis wanted,	0.25–0.35	0.50–0.80	0.25	0.040	0.040	...	0.80–1.00	0.25–0.50
Analysis found,	0.30	0.64	0.12	0.014	0.009	...	0.77	0.35

	Carbon.	Mn.	Chr.	Mo.
Preliminary from Laboratory	0.15	0.24	....	....
Points added	0.19	0.61	1.02	34.7
Total	0.34	0.85	1.02	34.7
Final	0.30	0.64	0.77	35.0
Loss	0.04	0.21	0.25	Gain 0.3

Remarks.—The ingots were heated to a good scaling temperature in soaking pits and rolled very good.

tively high cost of molybdenum alloys, and the uncertainty of the supply, together with the quality of the same. These latter features have now been eliminated and molybdenum steels should be even more generally used than nickel or the low grade nickel-chromium steels.

MANUFACTURE.

The manufacture of the alloy steels containing molybdenum is no more difficult than the same without the molybdenum. In fact, general experience indicates that the molybdenum increases the yield from ingot to shipped bars with less losses due to seams, pipeage and discards. These steels may be melted in the crucible, basic, or acid open-hearth and I believe, should it be desirable, in the Bessemer converter.

TABLE II.—RESULTS OBTAINED IN MOLYBDENUM HEATS.

Analyses Desired: Carbon, 0.23 to 0.30; Manganese, 0.60 to 0.80; Phosphorus, 0.035; Sulfur, 0.045 Silicon, 0.10 to 0.20; Chromium, 0.70 to 0.90; Molybdenum, 0.25 to 0.35.

Heat.	Analysis Found.							Molybdenum added, points.	Total Charge including additions, lb.	Ingot Product, lb.	Ingot Yield, per cent.
	Carbon.	Manganese.	Phosphorus.	Sulfur.	Silicon.	Chromium.	Molybdenum.				
1180	0.30	0.64	0.014	0.009	0.12	0.77	0.35	0.40	217 729	202 700	93.1
1181	0.31	0.61	0.009	0.013	0.15	0.70	0.35	0.35	200 410	180 760	90.3
1182	0.26	0.61	0.007	0.010	0.13	0.70	0.34	0.33	208 619	195 440	94.0
1183	0.24	0.71	0.021	0.014	0.13	0.87	0.26	0.30	206 943	201 500	97.4
1184	0.23	0.51	0.010	0.009	0.10	0.76	0.28	0.31	214 432	194 420	90.7
1185	0.23	0.49	0.009	0.009	0.13	0.84	0.32	0.31	213 345	204 280	95.5
1186	0.27	0.76	0.013	0.010	0.14	0.83	0.31	Furnace 0.29 Ladle 0.02	223 389	194 480	87.1
2448	0.25	0.55	0.005	0.009	0.13	0.65	0.28	0.31	212 996	198 660	93.3
2449	0.26	0.74	0.006	0.012	0.18	0.93	0.27	0.31	234 978	203 360	86.5
2450	0.26	0.74	0.010	0.011	0.20	0.73	0.31	0.31	233 239	209 400	89.8

If the crucible process is employed, the ferro-molybdenum is placed in the crucible with the last two-thirds of the charge, after the practice of making tungsten steels. Molybdenum powder similar to tungsten powder may be used, but on account of its high melting point and the impurities usually present, the recovery of molybdenum in the finished steel is less than is the case when the ferro-molybdenum with its melting point around 1550° C. for 50 to 60-per-cent molybdenum is used. Molybdenun powder, amorphous metal, melts between 2500 and 2550° C. and its uniform diffusion throughout the melt does not always take place. The advisability of using ferro-molyb-

denum is apparent. Calcium molybdate should never be used in the crucible process. Using the former, practically all the molybdenum added to the melt will be recovered in the ingot metal and this is also true of the basic or acid open-hearth practice.

The data in Table I, taken from the mill records of the open-hearth department, show the basic open-hearth practice

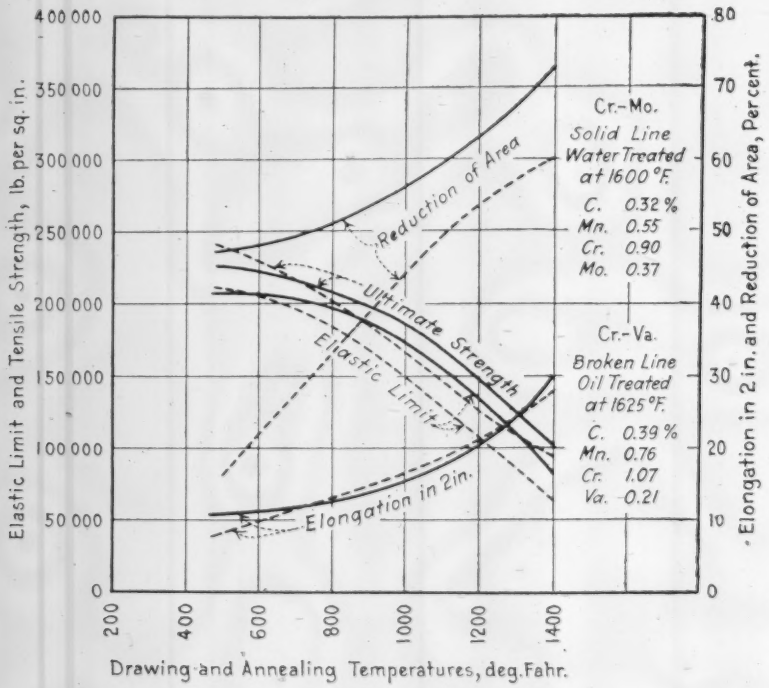


FIG. 2.—Comparison of Chrome-Molybdenum and Chrome-Vanadium Steels, $1\frac{1}{4}$-in. Square Bars Heat-Treated in Full Size, then Machined to 0.505 in. Diameter.

followed in producing some 6000 tons of the chromium-molybdenum steels.

Table II is a record of ten heats thus made, except that molybdenum steel scrap was used for part of the molybdenum addition. This scrap was introduced in the early part of the charge with the hot metal.

From this it is evident that the molybdenum does not go off into the slag when the steel is remelted as chromium and vanadium does, but behaves rather like nickel.

The yield through the various stages of manufacturing to the finished bars averaged as follows: ingot yield in melting, 87 per cent; billets yield in blooming, 80 per cent; bars in rolling, 94.4 per cent. In other words, 66 per cent of the metal charged into the furnace was obtained in finished bars.

In the production of molybdenum steel using the acid open hearth, the same general practice as that indicated for the basic open hearth was followed with similar results:

Analysis.	Carbon, per cent.	Manganese, per cent.	Chromium, per cent.	Nickel, per cent.	Molybdenum, per cent.	Molybdenum added, points.
Wanted	0.35 - 0.40	0.20 - 0.60	0.90 - 1.10	....	0.35 - 0.40	
Found	0.39	0.53	1.02	....	0.35	0.375
Wanted	0.35 - 0.40	0.20 - 0.60	....	1.50 - 2.00	0.35 - 0.40	
Found	0.40	0.45	....	1.61	0.43	0.425
Wanted	0.25 - 0.35	0.50 - 0.80	0.80 - 1.00	....	0.50 - 0.75	
Found	0.41	0.66	1.24	....	0.43	0.470

This last heat was made with calcium molybdate which was charged with cold pig iron in a container. The product was equal in every respect to that produced from ferro-molybdenum.

The uniformity of these steels is shown by Table III of analyses of four sets of drillings taken across top and bottom cuts of two 40-in. corrugated ingots. These drillings were numbered from the outside toward the center, as shown in Fig. 2.

TYPES OF MOLYBDENUM STRUCTURAL STEELS AND THEIR PHYSICAL PROPERTIES.

The types of these steels developed for structural purposes are:

CARBON-MOLYBDENUM.

	No. 1.	No. 2.	No. 3.
Carbon	0.10 to 0.50 per cent	0.10 to 0.50 per cent	0.10 to 0.50 per cent
Mn.	0.50 to 0.80 "	0.50 to 0.80 "	0.50 to 0.80 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

CHROME-MOLYBDENUM.

Carbon	0.10 to 0.50 per cent	
Mn.	0.50 to 0.80 "	
Phos.	not over 0.04 "	Same as the Carbon-Molybdenum but with
Sul.	" " 0.05 "	0.80 to 1.00 per cent Chromium added.
Chr.	0.80 to 1.00 "	
Mo.	0.25 to 0.50 "	

NICKEL-MOLYBDENUM.

Carbon	0.10 to 0.40 per cent	0.10 to 0.30 per cent	0.10 to 0.30 per cent
Mn.	0.50 to 0.80 "	0.30 to 0.60 "	0.30 to 0.60 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Ni.	1.00 to 1.50 "	1.00 to 1.50 "	1.00 to 1.50 "
or Ni.	1.50 to 2.00 "	1.50 to 2.00 "	1.50 to 2.00 "
or Ni.	2.00 to 3.00 "	....	....
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

CHROME-NICKEL-MOLYBDENUM.

Carbon	0.10 to 0.40 per cent	0.10 to 0.40 per cent	0.10 to 0.40 per cent
Mn.	0.45 to 0.75 "	0.45 to 0.75 "	0.45 to 0.75 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Chr.	0.45 to 0.65 "	0.45 to 0.65 "	0.45 to 0.65 "
or Chr.	0.80 to 1.00 "	0.80 to 1.00 "	....
Ni.	1.00 to 1.50 "	1.00 to 1.50 "	1.00 to 1.50 "
or Ni.	1.50 to 2.00 "	1.50 to 2.00 "	....
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

CHROME-MOLYBDENUM-VANADIUM.

Carbon	0.10 to 0.55 per cent	
Mn.	0.50 to 0.80 "	
Phos.	not over 0.04 "	
Sul.	" " 0.05 "	Same as Chrome-Molybdenum, but with
Chr.	0.80 to 1.00 "	0.15 per cent Vanadium added.
Mo.	0.25 to 0.50 "	
Va.	0.15 "	

MANGANESE-MOLYBDENUM.

	No. 1.	No. 2.	No. 3.
Carbon	0.10 to 0.55 per cent	0.10 to 0.55 per cent	0.10 to 0.55 per cent
Mn.	1.20 to 1.40 "	1.20 to 1.40 "	1.20 to 1.40 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

SILICO-MANGANESE-MOLYBDENUM.

Carbon	0.10 to 0.55 per cent		
Mn.	0.45 to 0.75 "		
Phos.	not over 0.04 "	Balance of Analysis	Balance of Analysis
Sul.	" " 0.05 "	same as No. 1	same as No. 1
Si.	1.75 to 2.00 "		
Mo.	0.25 to 0.50 "	0.50 to 0.75	0.75 to 1.00

From Table III, it is evident that molybdenum does not segregate or cause segregation.

The physical properties of these molybdenum steels can readily be appreciated from a study of Figs. 1 and 3–6, inclusive.

TABLE III.—ANALYSES OF DRILLINGS.[1]

Drilling.	Carbon.	Manganese.	Phosphorus.	Sulfur.	Silicon.	Nickel.	Chromium.	Molybdenum.
				No. 192724B1				
(Heat)	0.390	0.53	0.031	0.026	0.218	0.18	1.02	0.35
M1	0.380	0.51	0.031	0.023	0.235	....	1.00	0.37
M2	0.398	0.48	0.031	0.026	0.210	....	1.04	0.34
M3	0.426	0.47	0.035	0.028	0.204	....	1.06	0.38
M4	0.420	0.53	0.032	0.027	0.215	....	1.05	0.37
B1	0.368	0.50	0.030	0.021	0.206	....	1.02	0.39
B2	0.390	0.43	0.031	0.020	0.240	....	1.04	0.34
B3	0.380	0.51	0.030	0.023	0.240	....	1.02	0.37
B4	0.350	0.47	0.026	0.023	0.235	....	1.00	0.34
				No. 192734B1				
(Heat)	0.400	0.45	0.044	0.033	0.204	1.61	0.08	0.43
M1	0.398	0.46	0.035	0.032	0.195	1.68	....	0.44
M2	0.394	0.46	0.035	0.037	0.197	1.70	....	0.47
M3	0.402	0.46	0.038	0.042	0.198	1.70	....	0.48
M4	0.442	0.47	0.042	0.046	0.184	1.70	....	0.48
B1	0.374	0.46	0.033	0.023	0.179	1.68	....	0.45
B2	0.364	0.46	0.033	0.031	0.190	1.64	....	0.44
B3	0.312	0.44	0.031	0.029	0.174	1.68	....	0.40
B4	0.308	0.43	0.026	0.025	0.174	1.65	....	0.40

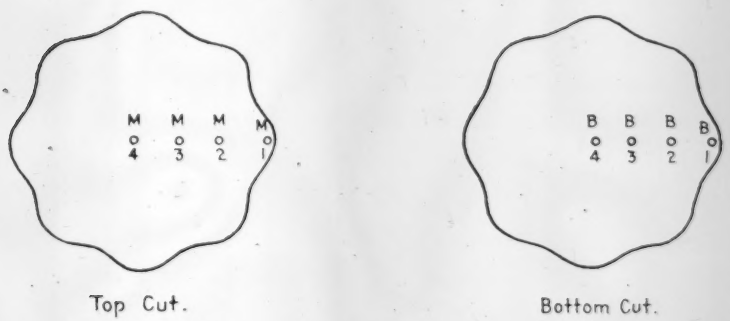


FIG. 2.—Drilling Locations at Top and Bottom of Ingots.

In all these figures, it will be observed in the case of the molybdenum steels, that as the drawing temperatures are raised up to 1000 to 1200° F. to further increase the toughness, the decrease in tensile strength and elastic limit values is less than

[1] Courtesy of R. M. Bird, Metallurgist, Bethlehem Steel Co.

CHROME-MOLYBDENUM.

Carbon	0.10 to 0.50 per cent	
Mn.	0.50 to 0.80 "	
Phos.	not over 0.04 "	Same as the Carbon-Molybdenum but with
Sul.	" " 0.05 "	0.80 to 1.00 per cent Chromium added.
Chr.	0.80 to 1.00 "	
Mo.	0.25 to 0.50 "	

NICKEL-MOLYBDENUM.

Carbon	0.10 to 0.40 per cent	0.10 to 0.30 per cent	0.10 to 0.30 per cent
Mn.	0.50 to 0.80 "	0.30 to 0.60 "	0.30 to 0.60 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Ni.	1.00 to 1.50 "	1.00 to 1.50 "	1.00 to 1.50 "
or Ni.	1.50 to 2.00 "	1.50 to 2.00 "	1.50 to 2.00 "
or Ni.	2.00 to 3.00 "	....	....
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

CHROME-NICKEL-MOLYBDENUM.

Carbon	0.10 to 0.40 per cent	0.10 to 0.40 per cent	0.10 to 0.40 per cent
Mn.	0.45 to 0.75 "	0.45 to 0.75 "	0.45 to 0.75 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Chr.	0.45 to 0.65 "	0.45 to 0.65 "	0.45 to 0.65 "
or Chr.	0.80 to 1.00 "	0.80 to 1.00 "	....
Ni.	1.00 to 1.50 "	1.00 to 1.50 "	1.00 to 1.50 "
or Ni.	1.50 to 2.00 "	1.50 to 2.00 "	....
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

CHROME-MOLYBDENUM-VANADIUM.

Carbon	0.10 to 0.55 per cent	
Mn.	0.50 to 0.80 "	
Phos.	not over 0.04 "	
Sul.	" " 0.05 "	Same as Chrome-Molybdenum, but with
Chr.	0.80 to 1.00 "	0.15 per cent Vanadium added.
Mo.	0.25 to 0.50 "	
Va.	0.15 "	

MANGANESE-MOLYBDENUM.

	No. 1.	No. 2.	No. 3.
Carbon	0.10 to 0.55 per cent	0.10 to 0.55 per cent	0.10 to 0.55 per cent
Mn.	1.20 to 1.40 "	1.20 to 1.40 "	1.20 to 1.40 "
Phos.	not over 0.04 "	not over 0.04 "	not over 0.04 "
Sul.	" " 0.05 "	" " 0.05 "	" " 0.05 "
Mo.	0.25 to 0.50 "	0.50 to 0.75 "	0.75 to 1.00 "

SILICO-MANGANESE-MOLYBDENUM.

Carbon	0.10 to 0.55 per cent		
Mn.	0.45 to 0.75 "		
Phos.	not over 0.04 "	Balance of Analysis	Balance of Analysis
Sul.	" " 0.05 "	same as No. 1	same as No. 1
Si.	1.75 to 2.00 "		
Mo.	0.25 to 0.50 "	0.50 to 0.75	0.75 to 1.00

From Table III, it is evident that molybdenum does not segregate or cause segregation.

The physical properties of these molybdenum steels can readily be appreciated from a study of Figs. 1 and 3–6, inclusive.

TABLE III.—ANALYSES OF DRILLINGS.[1]

Drilling.	Carbon.	Manganese.	Phosphorus.	Sulfur.	Silicon.	Nickel.	Chromium.	Molybdenum.
				No. 192724B1				
(Heat)	0.390	0.53	0.031	0.026	0.218	0.18	1.02	0.35
M1	0.380	0.51	0.031	0.023	0.235		1.00	0.37
M2	0.398	0.48	0.031	0.026	0.210		1.04	0.34
M3	0.426	0.47	0.035	0.028	0.204		1.06	0.38
M4	0.420	0.53	0.032	0.027	0.215		1.05	0.37
B1	0.368	0.50	0.030	0.021	0.206		1.02	0.39
B2	0.390	0.43	0.031	0.020	0.240		1.04	0.34
B3	0.380	0.51	0.030	0.023	0.240		1.02	0.37
B4	0.350	0.47	0.026	0.023	0.235		1.00	0.34
				No. 192734B1				
(Heat)	0.400	0.45	0.044	0.033	0.204	1.61	0.08	0.43
M1	0.398	0.46	0.035	0.032	0.195	1.68		0.44
M2	0.394	0.46	0.035	0.037	0.197	1.70		0.47
M3	0.402	0.46	0.038	0.042	0.198	1.70		0.48
M4	0.442	0.47	0.042	0.046	0.184	1.70		0.48
B1	0.374	0.46	0.033	0.023	0.179	1.68		0.45
B2	0.364	0.46	0.033	0.031	0.190	1.64		0.44
B3	0.312	0.44	0.031	0.029	0.174	1.68		0.40
B4	0.308	0.43	0.026	0.025	0.174	1.65		0.40

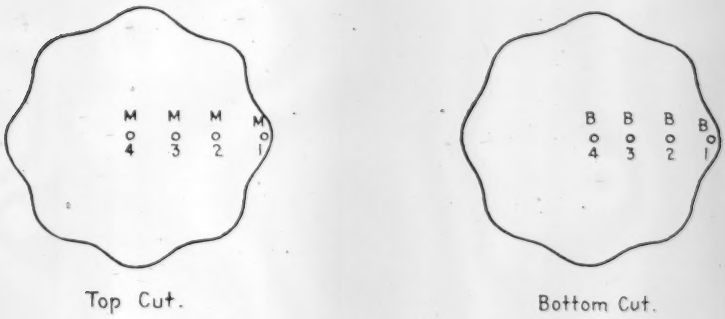


FIG. 2.—Drilling Locations at Top and Bottom of Ingots.

In all these figures, it will be observed in the case of the molybdenum steels, that as the drawing temperatures are raised up to 1000 to 1200° F. to further increase the toughness, the decrease in tensile strength and elastic limit values is less than

[1] Courtesy of R. M. Bird, Metallurgist, Bethlehem Steel Co.

is the case with the other steels compared. Furthermore, reductions of area which are the best measure of the toughness of the alloy steels are generally greater.

The molybdenum steels as a whole in the rolled or forged conditions show uniformly higher tensile strength and elastic limits with greater elongation and reduction of area.

	Tensile Strength, Lb. per Sq. In.	Elastic Limit, Lb. per Sq. In.	Elongation in 2 In., per Ct.	Reduction of Area, per Ct.
No. 1 Chrome-Molybdenum as rolled, 1 in. Round	140 000	105 000	15.0	32.0
No. 2 Nickel-Molybdenum as rolled, 1 in. Round	120 000	93 000	18.0	39.0

Analysis:

	Carbon.	Chromium.	Nickel.	Molybdenum.
No. 1	0.40	1.00	....	0.35
No. 2	0.40	....	1.50	0.40

The higher elastic limit of No. 1 as rolled, together with its easy machining qualities (for it machines as readily as the 70,000-lb.-per-sq.-in. elastic limit manganese steel used for gun barrels), recommends it for the purpose.

The effect of various quenching temperatures on the tension test values of the chrome molybdenum steels is shown by the following table and Fig. 7.

Quenching Temperatures.	Tensile Strength, Lb. per Sq. In.	Elastic Limit, Lb. per Sq. In.	Elongation in 2 In., per Cent.	Reduction of Area, per Cent.
1550° F.	160,925	156,625	18.0	62.2
1600° F.	155,850	149,925	17.5	60.2
1650° F.	156,375	145,775	17.0	60.2
1700° F.	153,450	141,570	17.0	60.1
1750° F.	154,350	142,500	18.0	60.0
1800° F.	154,900	144,000	17.5	59.0

Drawing Temperature: 1000° F. Quenching medium: water. ¾-in. Round Bar.
Analysis: 0.30 per cent Carbon, 0.70 per cent Chromium, 0.35 per cent Molybdenum.

A microscopic study of the structure of nearly all of these steels shows great similarity in that, when quenched and drawn from 350 to 1100° F., they show a fine uniform distribution of the constituents; so much so that the structure of the specimen drawn at 1100° F., which presumably contains ferrite and pearlite,

cannot be distinguished from that drawn at 350° F. except in the case of the lower molybdenum-content steels, which show, when drawn as high as 700° F., a martensitic or pseudo martensitic structure. Otherwise even these are alike as the following studies show. When heated after quenching to 1400° F., the ferrite separates out distinctly from the pearlite, which latter takes a more pearlitic structure. In other words, the steel becomes annealed.

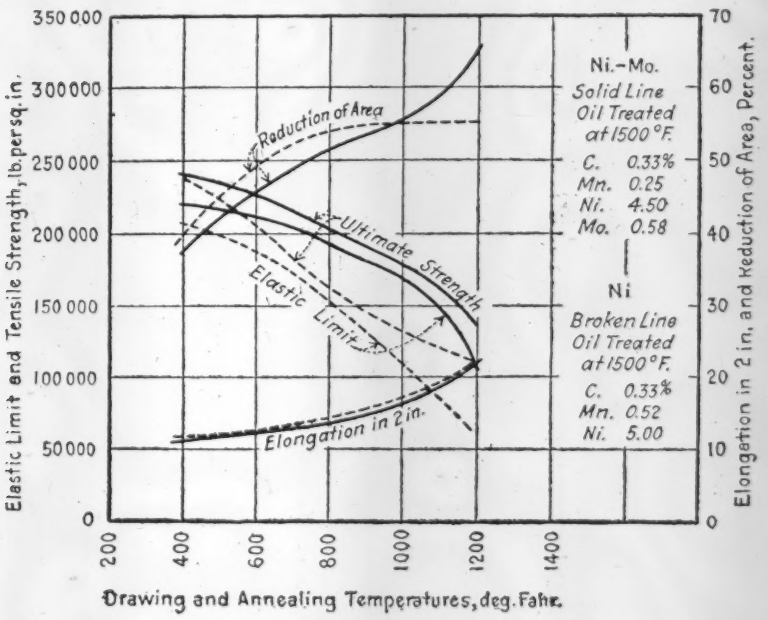


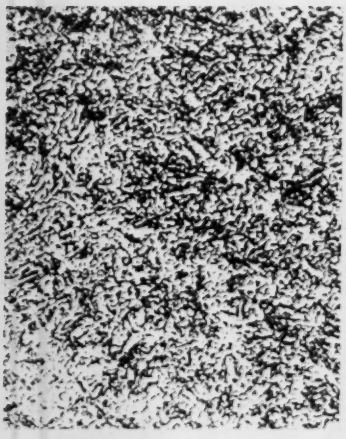
FIG. 3.—Comparison of Nickel-Molybdenum and Nickel Steels, 1⅛-in. Round Bars Heat-Treated in Full Size, then Machined to 0.505 in. Diameter.

PHOTOMICROGRAPHS.

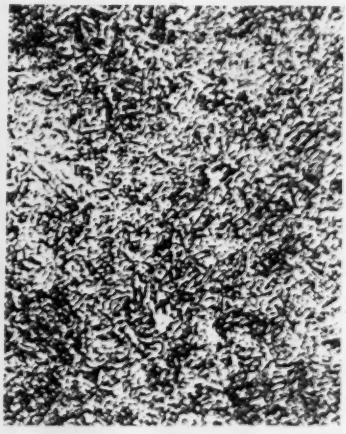
Plates I to III are photomicrographs of molybdenum steels heated to 1600° F. and quenched in oil.

Swinden's[1] investigations of the recalescent curves, electrical resistivity, hardness of annealed and quenched specimens of carbon molybdenum steels led him to conclude, and the evidence

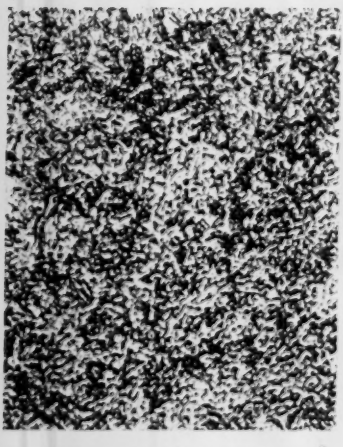
[1] *Journal*, Iron and Steel Inst., Carnegie Scholarship Memoirs, Vol. V, 1913.



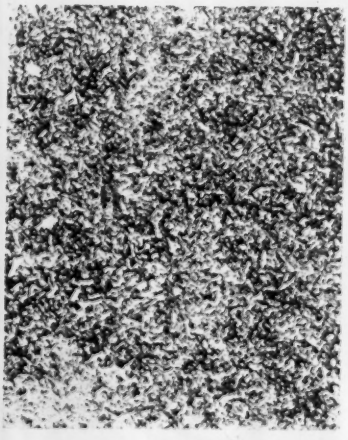
Drawn at 350° F.



Drawn at 500° F.

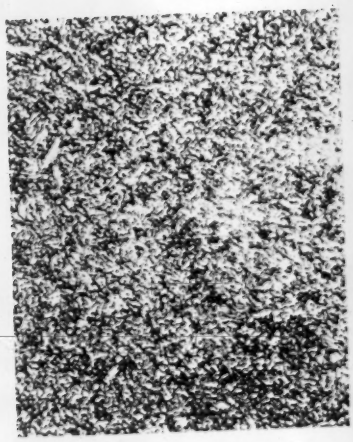


Drawn at 700° F.

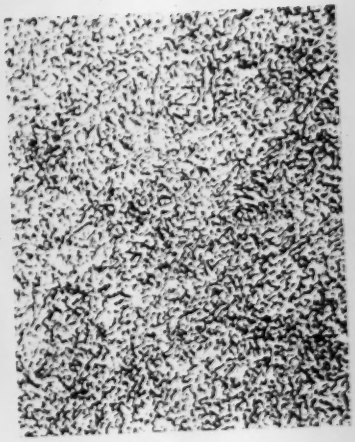


Drawn at 900° F.

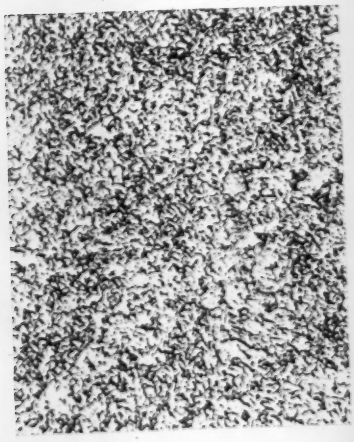
PLATE I.—Photomicrographs of Samples, Oil Treated from 1600° F. and Drawn at the Temperatures Indicated. Transverse Sections, Etched with 10-per-cent Nitric Acid and Alcohol (× 400).



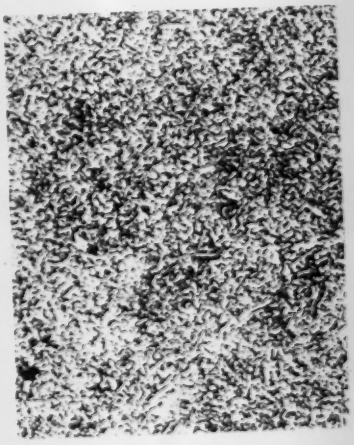
Drawn at 1100° F.



Drawn at 1200° F.



Drawn at 1300° F.



Drawn at 1400° F.

PLATE I *(continued)*.—Chemical Composition: Carbon 0.39, Manganese 0.48, Chromium 1.05, Vanadium 0.17, Molybdenum 0.87.

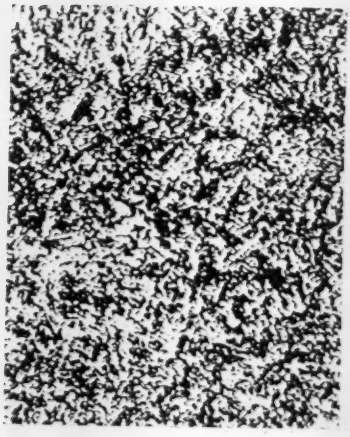
Drawn at 350° F.

Drawn at 500° F.

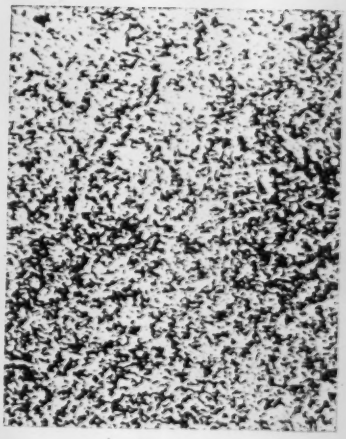
Drawn at 700° F.

Drawn at 900° F.

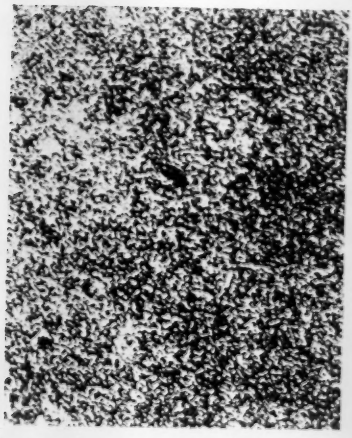
PLATE II.—Photomicrographs of Samples, Oil Treated from 1600° F. and Drawn at Temperatures Indicated. Transverse Sections, Etched with 10-per-cent Nitric Acid and Alcohol (× 400).



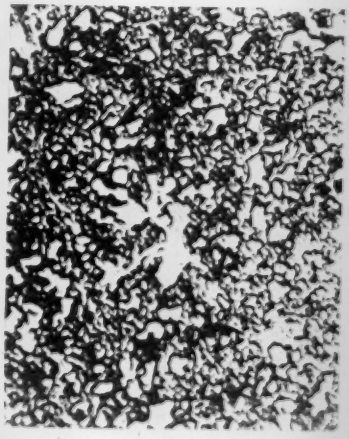
Drawn at 1100° F.



Drawn at 1200° F.



Drawn at 1300° F.



Drawn at 1400° F.

PLATE II (*continued*).—Chemical Composition: Carbon 0.25, Manganese 0.48, Phosphorus 0.019, Sulfur 0.009, Silicon 0.18, Chromium 0.95, Molybdenum 0.73.

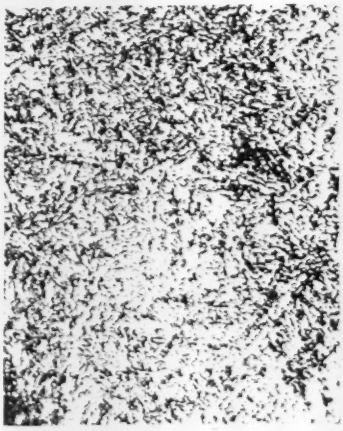
Drawn at 350° F.

Drawn at 500° F.

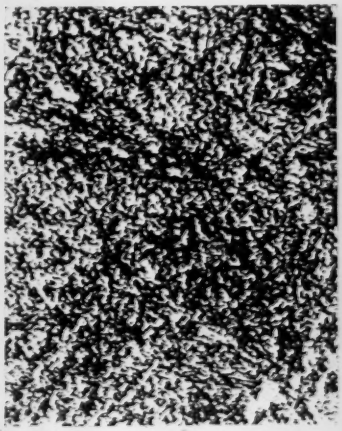
Drawn at 700° F.

Drawn at 900° F.

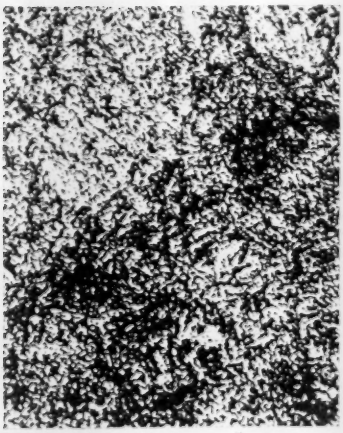
PLATE III.—Photomicrographs of Samples, Oil Treated from 1600° F. and Drawn at Temperatures Indicated. Transverse Sections, Etched with 10-per-cent Nitric Acid and Alcohol (× 400).



Drawn at 1100° F.



Drawn at 1200° F.



Drawn at 1300° F.

Drawn at 1400° F.

PLATE III (*continued*).—Chemical Composition: Carbon 0.32, Manganese 0.49, Phosphorus 0.04, Sulfur 0.012, Silicon 0.10, Chromium 0.90, Molybdenum 0.40.

submitted strongly supports him, that the molybdenum in the absence of chromium or of an excess of the normal amount of manganese, is diffused throughout the ferrite of the steel, to which it imparts greater toughness. In the presence of chromium or manganese it very probably also forms double carbides, imparting additional hardness and strength. Hence the combination of greater strength and greater toughness shown by these latter steels.

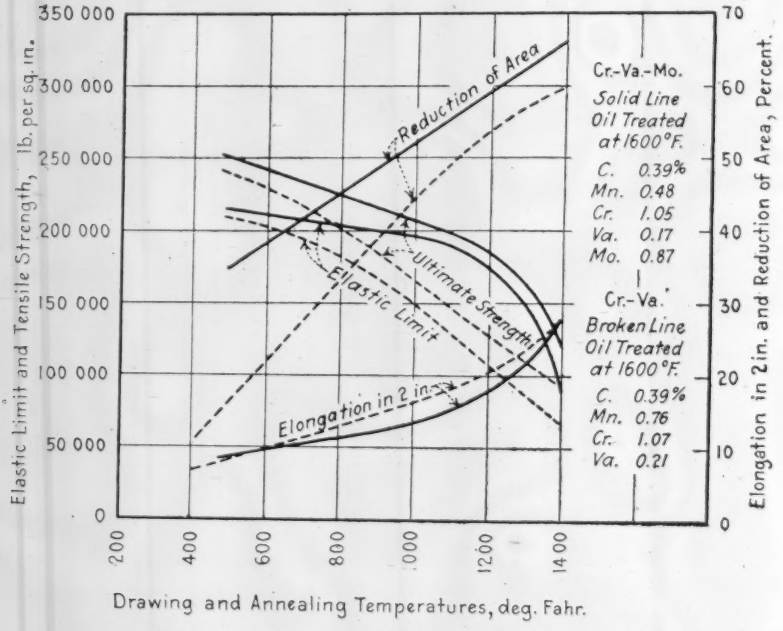


FIG. 4.—Comparison of Chrome-Vanadium-Molybdenum and Chrome-Vanadium Steels, 1⅛-in. Round Bars Heat-Treated in Full Size, then Machined to 0.505 in. Diameter.

Our study of the few heating and cooling curves of these molybdenum steels for structural purposes discloses the phenomenon pointed out by Swinden as belonging to the molybdenum steels investigated by him: namely, that upon heating to a temperature of 810° C. (1490° F). and higher, the Ar_1 point was lowered to around 500° C. (932° F.).

Swinden noted the recovery of the normal point of these

molybdenum steels so heated followed upon reheating repeatedly to 800° C. (1472° F.) or soaking at 800° C. (1472° F.). In other words, the 1 to 8 per cent molybdenum steels when heated to beyond 800° C. (1472° F.) result in the solution of the carbide of iron and molybdenum with the formation of a definite compound, which upon cooling first breaks up into Fe_3C giving the normal cooling curve points, and later as the cooling progresses, breaks

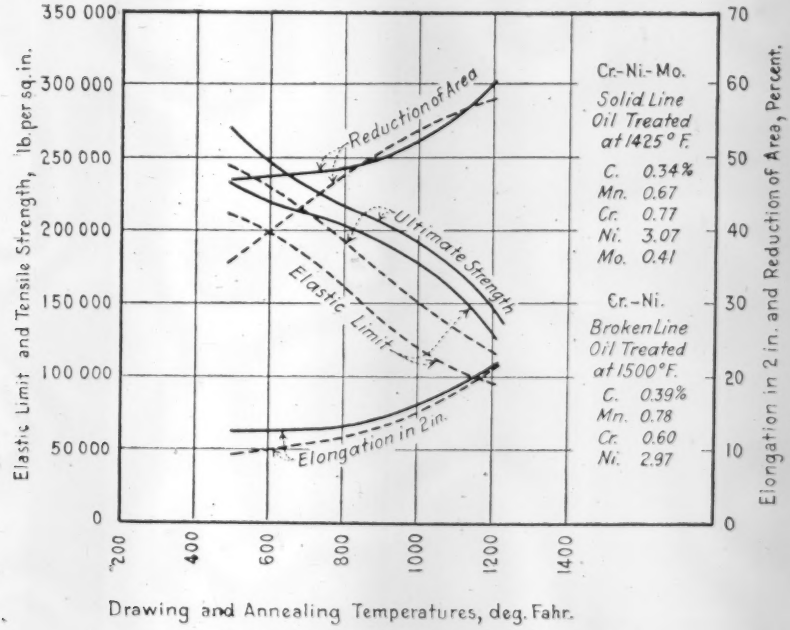


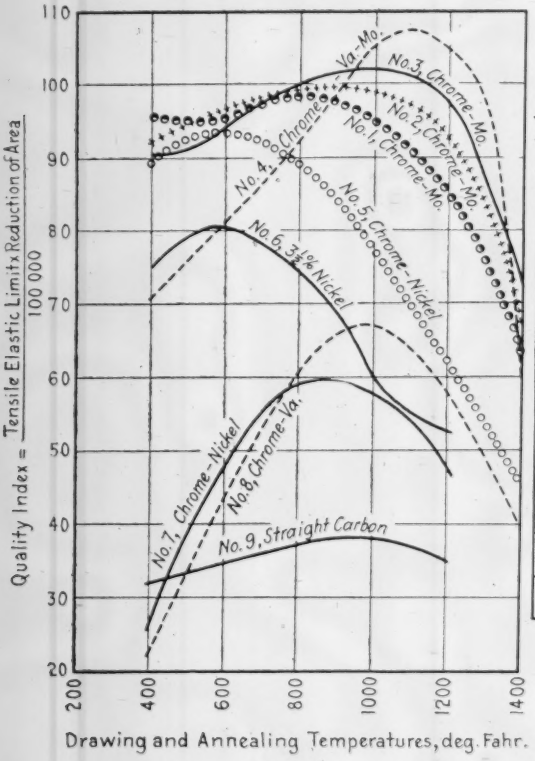
FIG. 5.—Comparison of Chrome-Nickel-Molybdenum and Chrome-Nickel Steels, 1-in. Round Bars Heat-Treated in Full Size, then Machined to 0.505 in. Diameter.

up into a molybdenum iron and iron compound which can only be broken up into the normal iron with molybdenum in solution, upon repeated heatings as pointed out. This molybdenum iron and iron compound is therefore difficult to disassociate and if the steel be quenched from the hardening temperature, it is fixed and but slowly reverts to the normal state, upon reheating. This phenomenon, as stated, we have found in these steels with

0.25 to 0.50 per cent molybdenum and it is this which causes the high tensile strength and elastic limits to extend over a long range of drawing temperatures, producing the flatness shown by the curves.

COMMERCIAL FEATURES.

From the steel maker's point of view, the production of these steels is commercially practicable, as what has been presented



All Steels Properly Hardened and Drawn or Annealed as Indicated.

No.	C.	Cr.	Ni.	Mo.	Va.
1	0.25/0.35	0.75/1.00		0.25/0.50	
2	0.25/0.35	0.80/1.00		0.50/0.75	
3	0.25/0.35	1.00/1.20		0.75/1.00	
4	0.30/0.40	1.00/1.20		0.75/1.00	0.20
5	0.30/0.40	1.00/1.20	3.00/3.25		
6	0.30/0.40		3.25/3.75		
7	0.30/0.40	0.50/0.60	1.00/1.20		
8	0.30/0.40	1.00/1.20			0.20
9	0.35/0.45				

FIG. 6.—Comparative Quality Curves of Molybdenum and Other Alloy Steels.

under manufacture indicates to be the case; and now that the supply of molybdenum ore in large quantities is assured, these steels will be widely used. They cost less per pound of alloy used in their production than 3.5-per-cent nickel steel. For

example, the nickel in a pound of 3.5-per-cent nickel steel at 40 cents per lb. costs 1.4 cents; in 1.0-per-cent chromium, 0.25 to 0.50-per-cent molybdenum (0.40 per cent added) steel, with chromium at 20 cents per lb. and the molybdenum at $2.00 per lb., the alloys cost but 0.33 cents for the chromium and 0.8 cents for molybdenum, a total of 1.13 cents.

The physical qualities, such as forgeability, machineability,

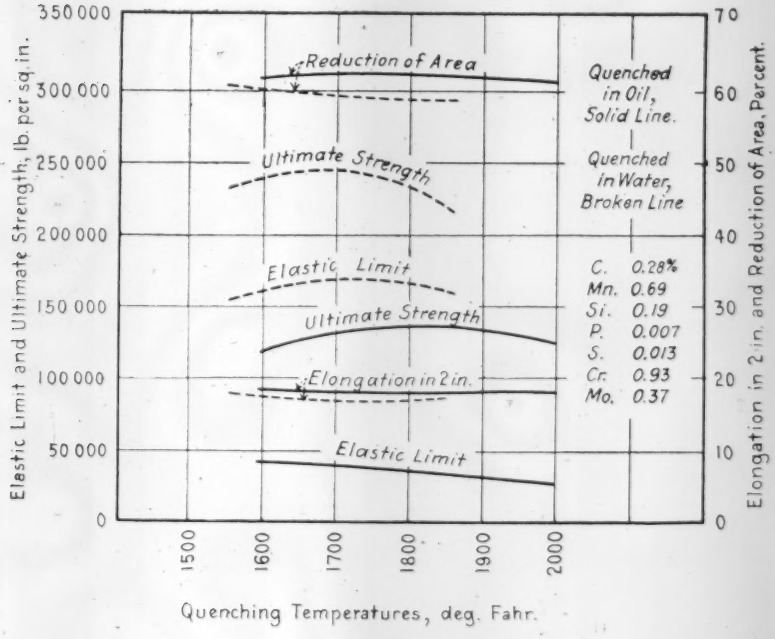


FIG. 7.—Effect of Quenching $1\frac{3}{16}$-in. Square Bars in Oil and Water from Various Temperatures, Hardened and Drawn to 1000° F. in Full-Size Section, then Machined to 0.505 in. Diameter.

responsiveness to heat treatment, together with the great strength and toughness of these steels are such that for structural steel elements such as those entering into the manufacture of machines, automobiles, aeroplanes, etc., where strength and toughness are necessary to meet service conditions, they will be used with the best of results. Among such elements may be mentioned gears, crank shafts, connecting rods, shafts, springs, cams,

bearings, etc. Thus Swinden's prophesy of 1913 has been realized and that at a time most opportune, for we are faced with a shortage of some of the alloys hitherto used for the production of the high tensile strength value steels, which are now so costly.

Molybdenum has been introduced into cast iron with the result that the texture of the iron seems to be very much improved, being finer, tougher and showing an increase in its tensile strength, as the table below shows:

	Brinell Hardness.	Tensile Strength, lb. per sq. in.
No. 6 cast iron containing no molybdenum....	236	32 500
No. 7 cast iron containing 2 per cent molybdenum.....	277	36 300
No. 8 cast iron containing 4 per cent molybdenum.....	311	38 400

The machining properties of both these cast irons containing molybdenum are very markedly superior to that of No. 6. The use of molybdenum in malleable castings seems to offer quite some promise, although the experiments are too few to make any definite statements, but it would appear that there is an increase in tensile strength and toughness of such castings, and where they can be heat treated, there is a marked improvement in the strength and toughness.

Most of the work of investigating the steels has been done by Mr. J. W. Weitzenkorn and I am deeply indebted to him for his most valuable assistance, for which I wish to make grateful acknowledgment.

DISCUSSION.

A MEMBER.—Can Mr. Sargent tell us whether the molybdenum is contained in the ferrite or exists as a carbide? A Member.

Mr. G. W. SARGENT.—According to Swinden's investigations, it exists in the ferrite of carbon molybdenum steels, but with chromium present, I think it prevails in both places. Mr. Sargent.

MR. R. P. DEVRIES.—I should like to ask Mr. Sargent what basis he has for that statement? I do not think the micrographs indicate that at all. Mr. Devries.

MR. SARGENT.—I would refer Mr. Devries to Swinden's article published in 1913, or the one just previous to that, in which he made a very extensive series of investigations to determine whether the molybdenum was in the ferrite or in the pearlite. The steels were free from chromium and of low manganese content, so that the formation of double carbides would in all likelihood not occur or at least would be less likely to be present. Swinden's deductions were to the effect that the molybdenum combines in those steels with the ferrite and not the carbide of iron. Mr. Sargent.

When chromium is introduced, we all know that chromium carbides form and it is likely that the chromium double carbides carry with them the molybdenum and therefore, molybdenum probably occurs in both ferrite and carbide in the chrome-molybdenum steels. I am pretty sure of this, although I have no positive data to prove it.

MR. M. P. DAVIS.—I should like to ask Mr. Sargent in regard to cast iron, whether the ferro-molybdenum was added to the charge or to the ladle, when 2 and 4 per cent of molybdenum were present in the finished casting. Mr. Davis.

MR. SARGENT.—It was added in the runner during the tapping from cupola to ladle. Mr. Sargent.

MR. DAVIS.—I have made some preliminary tests on the addition of ferro-molybdenum to semi-steel mixtures and find the same increase in tensile strength that the author has reported. Sixty per cent ferro-molybdenum was added to the ladle in an amount sufficient to give 0.5 per cent molybdenum in the finished castings. This produced a decided increase in the tensile strength and Brinnell hardness; although with the increase in Brinnell Mr. Davis.

Mr. Davis. hardness, the machining qualities of the metal seemed to be much better.

Mr. Sargent. MR. SARGENT.—I might state that 50 per cent ferro-molybdenum was used in our experiments with cast iron.

Mr. Woodward. MR. R. WOODWARD.—I should like to ask Mr. Sargent if he has had any experience with molybdenum in combination with high silicon in steel. At the Bureau of Standards, we have been making a series of tests on nickel-silicon steel, about 3.5 per cent nickel and in the neighborhood of 1.25 per cent silicon. The majority of the tests show tensile strengths of 300,000 lb. per sq. in. and above, with a reduction in area of 30 or 35 per cent. We find that the addition of molybdenum in some of these makes the specimens so brittle that we cannot get any satisfactory tension tests on them. Has Mr. Sargent's experience been similar?

Mr. Sargent. MR. SARGENT.—I have not made tests on any high straight silicon steel. The highest percentage of silicon was 1.75 to 2.10 per cent and with manganese present in slightly over the usual amount, about 0.80 per cent. In such tests a decided improvement in the machining quality of the steel has been observed, with an increase in the reduction of area and likewise in the elastic limit and tensile strength.

Mr. White. MR. J. A. WHITE.—I should like to ask Mr. Sargent in regard to the torsional values of the steel; are they not rather low in comparison with some of the other steels? For instance, in the use of automobile crank shafts and driving shafts?

Mr. Sargent. MR. SARGENT.—I have made one or two torsion tests that astounded me. In one case the bar was gripped 18 in. between supports and twisted through thirteen complete revolutions before it broke. That was an oil-treated, annealed chrome-molybdenum steel of the No. 3 type shown on the comparison chart, annealed at approximately 1400° F. I do not remember the tensile strength of that steel. I have had some molybdenum steel that showed a reduction of area as high as 82 per cent. The reduction of area, of course, is indicative of the value of the steel under torsion.

Mr. White. MR. WHITE.—I refer particularly to the point of elastic torsion, not the ultimate torsion.

Mr. Sargent. MR. SARGENT.—The elastic torsion is high corresponding to the elastic limit of the steel under tension.

A NOTE ON STRESSES CAUSED BY COLD ROLLING.[1]

By Henry M. Howe and Edward C. Groesbeck.

Introduction.

Professor A. E. White[2] held that a given total reduction of the thickness of brass condenser tubes was given better by many light drafts than by a few heavy ones, an opinion as to which so competent an observer as Mr. W. R. Webster expressed doubt. Later experiments by Mr. Webster[3] were inconclusive.

In studying the effect of variations in the degree of reduction per pass, we should know, among other things, how they affect the intensity of the stresses set up in the metal by the rolling. To that end we have made the experiments here described. As a matter of convenience we operated on strips of soft sheet steel, both because this is a more important material than brass, and because we believe that what is true of one is true qualitatively of the other, and indeed of most metallic masses which resemble them generally in their mechanical properties.

Experimental Procedure.

We rolled cold a series of pairs of strips of low-carbon sheet steel as sketched in Figs. 1 and 2, reducing the several strips from their initial thickness of 0.035 in. to 0.029 in., using in some cases six heavy reductions or passes, in others ten passes of intermediate severity, and in still others thirty-one light passes. We inferred the relative intensity of the residual stresses from the sharpness of the curvature thus induced in the strips, as shown in Fig. 2. Further details of procedure are as follows:

The material consisted of common cold-rolled soft sheet steel 0.036 in. in thickness. All the strips were cut from a single sheet. Each of them was 3 in. long and 0.5 in. wide. All were ground to size along the edges to remove any part that

[1] Published by permission of the Director of the Bureau of Standards.

[2] A. E. White, "An Investigation Leading to Specifications for Brass Condenser Tubes," *Proceedings*, Am. Soc. Test. Mats., Vol. XVI, Part II, p. 151 (1916).

[3] W. R. Webster, "Light versus Heavy Reduction in Cold Working Brass," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 157 (1917).

was affected by cutting them from the sheet. They were next annealed at 690-740° C. for 2 hours, and were then ground down to a thickness of 0.035 in.

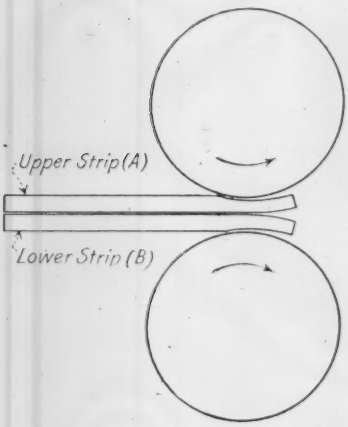


FIG. 1.—Strips Entering the Initial Pass.

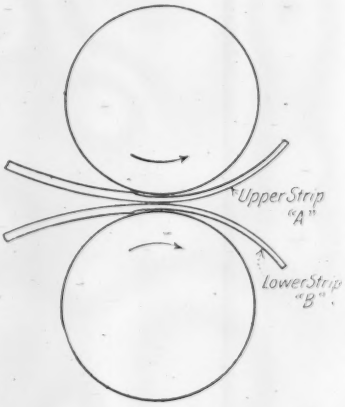


FIG. 2.—A Later Pass.

FIGS. 1 AND 2.—Sketches Showing How the Spring or Arching is Caused in Two Superposed Strips by the Residual Stress Caused by Cold Rolling. The thickness of the strips is exaggerated for clearness of illustration.

The rolls were 2 in. in diameter and 3 in. long.

The Curvature.—The strips were rolled in pairs, one strip being superposed on the other as in Figs. 1 and 2, and the resultant curvature was determined after each pass both by

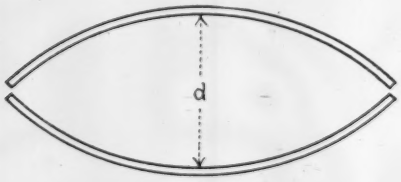


FIG. 3.—Sketch Showing Method of Measuring the Combined Spring of the Two Members of Each Pair of Strips. (See Fig. 4.)

measuring the "rise" or arching of each strip, and also by measuring the total distance between the two members of each pair at their greatest distance apart, d, when set together as in Fig. 3.

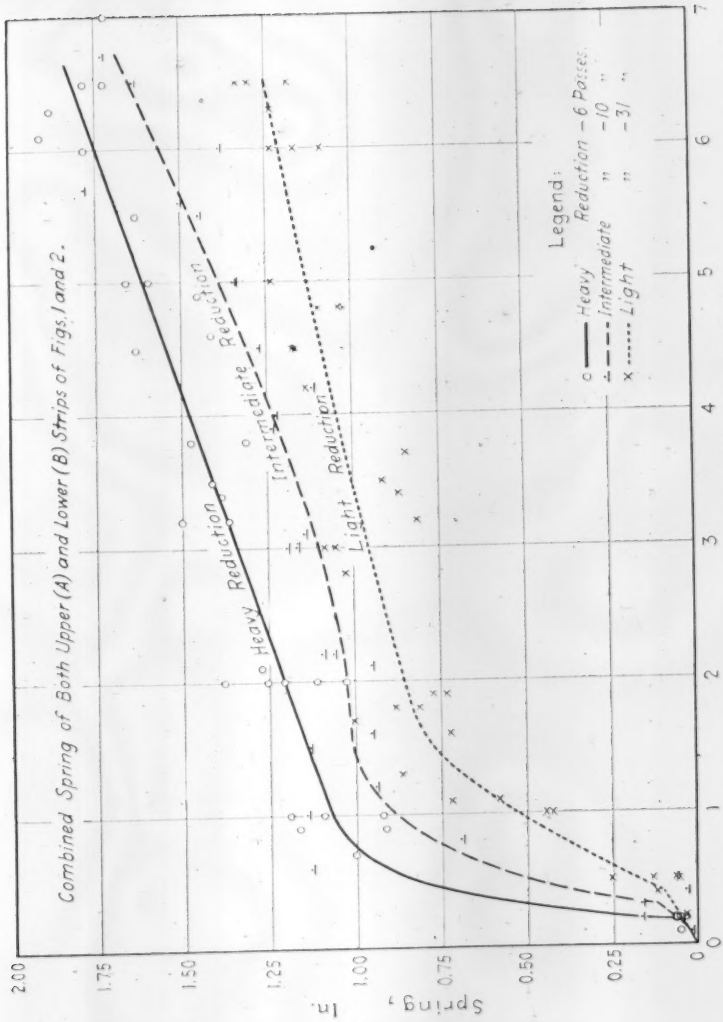


FIG. 4.—Increase in Combined Spring Produced by Successive Passes in Both Strips of Each Pair of Superposed Strips.

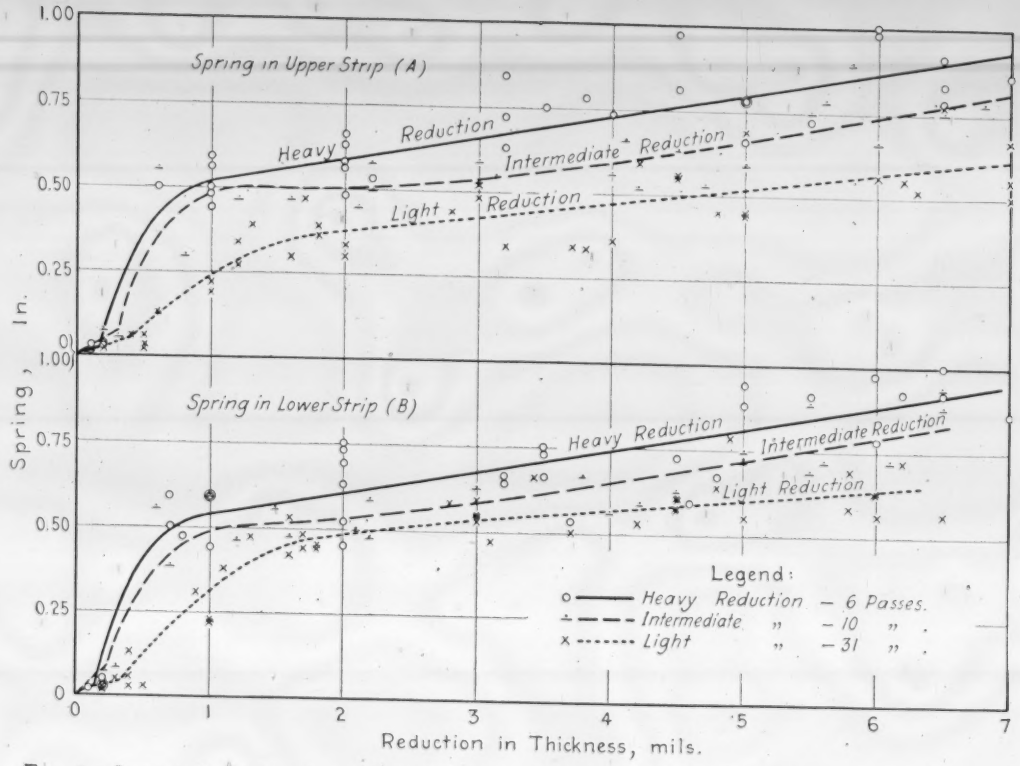


FIG. 5.—Increase in Spring Produced by Successive Passes in the Individual Strips of Each Pair of Superposed Strips.

The width of the strips did not change measurably in any case throughout the whole course of the rolling.

The elongation of the strips as measured along their convex faces was found to be directly proportional to the reduction, and independent of the number of passes by which it was brought about.

The total number of strips represented by these results was twelve for the heavy, six for the intermediate, and fourteen for the light reductions.

THE RESULTS.

As shown in Figs. 4 and 5, the spring caused by a given total reduction increases with the amount of reduction per pass. The concordance in these first crude experiments we believe suffices to establish the principle, but more elaborate experiments would be needed to determine the quantitative relations between the effects of light and heavy reductions. In particular, the length of the strips used in the experiments, 3 in., was too small to enable us to enter them always strictly normally to the vertical plane passing through the axis of the rolls, and hence there was a tendency for the strips to roll diamondwise. This tendency was met by entering the strips slightly obliquely in the following pass.

THE EXPLANATION.

Flow of Metal Due to Skin Friction.—We refer the greater stress caused by the heavier reductions to the greater skin friction produced between the strips and the rolls.

To refresh our memory as to what occurs in rolling, let us suppose that a solid bar *OABDHE*, Fig. 6, enters the rolls so that its face *CG* reaches the plane of their axes, and that its segments *ABC* and *HDG* are squeezed away from the original position by the pressure, with the result that the upper surface of the piece takes the shape *OKC* and the lower surface the shape *ELG*. What becomes of this metal initially in *ABC* and *HDG*? It flows away from the pressure of the rolls. The vertical component of the flow from each roll is in great part neutralized by the resistance of the other roll, so that most of the flow follows the horizontal component, and that the metal flows backwards. For simplicity, the slight bulging up and down at *K* and *L* may here be ignored.

The friction of the faces of the rolls impedes the backward flow of the metal in immediate contact with them, with the result that the rate of backward flow increases from the upper and lower surfaces of the piece AB and HD towards its axis PN. In a solid bar thus rolled, this progressive difference in the degree of backward flow from surface to axis results in residual stress. But if we suppose that this solid bar $OBDE$ is slit in two along PN so as to give the conditions of our experiments, this same progressive difference causes each of the two strips to bend, so that its face which is next to the roll becomes concave, and that which originally lay along PN becomes convex. The degree of this convexity measures roughly the excess of backward flow along PN over that at the upper and lower faces OAB and EHD.

This brings us to our explanation of the phenomenon

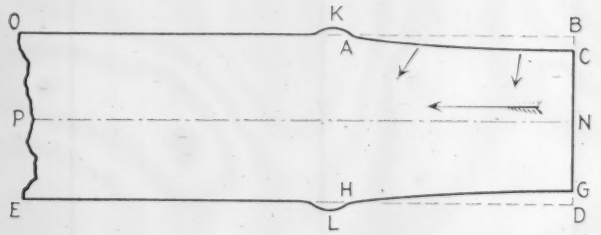


FIG. 6.—The Backward Flow of Metal During Reduction is Greater Along the Axis than on the Surface of the Bar, and Approximately in the Direction Shown by the Arrows.

observed, that for a given total reduction the spring increases with the severity of reduction in the individual passes, or, in other words, is approximately inversely as the number of passes used to cause the given reduction. The friction of the face of the rolls is due chiefly to their roughness. Each of the thousands of immeasurably small protuberances on the face of the rolls bites into the metal, and impedes its flowing past them, impedes it but does not arrest it, as is proved by the progressive lengthening of even the concave faces of the strips. Clearly the greater the reduction in a given pass, the greater is this frictional impediment to the backward flow at the surface; hence the greater is the ratio of the axial to the surface flow; hence the greater the internal stress in a solid bar thus rolled, and the greater the convexity induced in a pair of strips as rolled in these experiments. The explanation thus resides wholly in

the increase of the ratio of axial to surface flow caused by increase of surface friction due to increased reduction per pass.

The Progressive Flattening of the Curves of Figs. 4 and 5.—This flattening represents a progressive lessening of the increment of curvature caused in successive passes by the friction of the rolls. A tentative explanation is that, as the strip grows progressively stiffer because of the plastic deformation, it offers progressively greater resistance to the tendency of the friction of the rolls to increase its curvature.

Confirmatory Evidence.—Mr. E. H. Peirce[4] of the American Steel and Wire Co. finds that a greater total reduction can be endured without rupture in wire-drawing with a larger number of light drafts than with a smaller number of heavy ones. Moreover, the tensile strength, the ductility as indicated by the various toughness tests, and the elastic limit as indicated by the ability of the wire when in helical springs to endure compression without taking permanent set, are greater for a given total reduction when this is caused by a larger number of light drafts. Since internal stress tends to lessen all three of these properties, these observations are in harmony with ours.

Extrapolation of Results.—It may be assumed provisionally that what is true of cold-rolling is true also of drawing through a die, because the action of the rolls approximates that of a rolling die, the grip which draws the metal forward being given by the surface friction of the rolls instead of by a clutch as in wire, spring, and tube drawing.

SUMMARY.

1. When the thickness of a pair of strips is reduced by a given amount by cold-rolling; the internal stress, as inferred from the convexity which these strips assume, increases with the amount of reduction per pass. This is ascribed to the skin friction of the rolls.

2. As the rolling progresses the rate of deflection decreases, perhaps because the progressive increase of the stiffness of the strips enables them to resist better the bending effect of the skin friction.

3. The elongation is proportional to the reduction and independent of the number of passes.

[4] Private communication, March 20, 1919.

DISCUSSION.

Mr. Woodward. MR. R. W. WOODWARD (*presented in written form*).—This paper deals with a subject of importance to all interested in the cold working of metals and especially of those non-ferrous alloys in which it has been repeatedly shown that the presence of initial internal stresses resulting from cold working are so detrimental to the material when placed in service. As mentioned by the authors, the effect of making a certain reduction in a large number of passes or in a few passes has been a matter of controversy.

At the 1918 meeting,[1] Mr. P. D. Merica and the writer presented some initial stress diagrams for some cold-drawn brass rods furnished by Mr. W. R. Webster of the Bridgeport Brass Co. No. 1 of these rods was stated to have been given the final reduction to size in one pass, whereas No. 5 received the same reduction in 5 passes. The residual stresses in the two bars are strikingly different, No. 1 having a maximum tensile stress at the surface of 26,500 lb. per sq. in. and an average stress of 18,750 lb. per sq. in., whereas No. 5 had a maximum tensile stress of 14,400 lb. per sq. in. and an average of only 4930 lb. per sq. in. The reduction data were not given at that time since Mr. Webster suspected a possible confusion of the specimens as the data obtained did not correspond to his views. These facts are now presented for what they are worth in view of this latter evidence.

It is generally stated in discussions[2] of stresses introduced by cold working that in drawing, tensile stresses remain at the surface and compressive stresses in the interior, while rolling and forging leave a state of compression at the surface.

An analysis of the results obtained by Howe and Groesbeck would imply that tension would exist in the surface of a rolled sheet. Their method also assumes that two strips rolled together

[1] P. D. Merica and R. W. Woodward, "Initial Stresses and Corrosion Cracking", *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 165 (1918).

[2] E. Heyn, "Internal Stresses in Cold-Wrought Metals, and Some Troubles Caused Thereby", *Journal* Inst. Metals, *Vol. 12*, p. 3 (1914). P. D. Merica and R. W. Woodward, "Failure of Brass", *Technical Paper No. 82*, Bureau of Standards (1917).

act the same, at least in the formation of strains, as a solid strip. A few simple experiments were accordingly carried out to ascertain the exact conditions obtained in rolling such strips. Mr. Woodward.

A piece of commercial sheet brass, 0.063 in. thick, was taken and part rolled to half the original thickness, namely 0.032 in. These were annealed dead soft (Scleroscope = 6) and cut into strips $\frac{1}{2}$ by 3 in. The thick strip and a pair of the thin strips were then rolled, in one pass, to a thickness of 0.053 in. Naturally the solid strip remained flat, while the thin strips arched, similar to those of Howe and Groesbeck, the total amount of arching being 1.40 in. The scleroscope hardness of both solid and divided strips was 18–20.

The solid strip was next covered with paraffin except on one surface and one half the thickness removed by etching with 1 : 2 nitric acid. The strip was then found to have a curvature in the same direction as the thin strips, but amounting to only 0.16 in. The computed stresses in both cases would be 34,000 lb. per sq. in. maximum tension at the surface for the superimposed strips and 5000 lb. per sq. in. tension for the solid strip.

Of course the value for the double strips means but little since it is beyond the elastic limit, which fact can also be shown by flattening and releasing the arched strips, in which case the combined arching is reduced to 0.60 in. corresponding to a tensile stress of 15,000 lb. per sq. in. (*i. e.* the elastic limit).

By rolling two similar sheets of lead in one pass from 0.076 to 0.048 in. in thickness, a total arching of 2.1 in. was obtained, the curvature nearly corresponding to that of the rolls. The large curvature in this case is interesting, since we know that lead can retain practically no residual stresses.

The above tests still indicated tension only at the surface due to cold rolling. A piece of the annealed sheet brass 3 in. square was then similarly rolled and $\frac{1}{2}$-in. strips, both longitudinal and transverse to the direction of rolling, were removed and the stresses determined in both by the method previously described[1] of removing one-quarter of the thickness by etching. The measurements are necessarily approximate because of the small specimens used, but indicated for the strip at right angles to the direction of rolling 15,000 lb. per sq. in. compression at the

[1] See Merica and Woodward, *loc. cit.*

Mr. Woodward. surface and for the longitudinal strip 15,000 lb. per sq. in. tension at the surface.

By rolling two such square sheets superimposed no curvature in a transverse direction could be detected, although the sheets arched longitudinally as formerly.

From these few simple experiments the following conclusions can be drawn:

1. Two strips superimposed in rolling do not behave as a solid strip due to the lack of cohesion in the central layers.

2. The "arching" obtained by rolling superimposed strips, although probably tied up with the formation of initial strains, is not entirely due to that cause and is effected only by the longitudinal surface tensile stresses.

3. In cold rolling sheets, surface tensile stresses are set up in the direction of rolling and compressive stresses at right angles to the direction of rolling.

Mr. Webster. MR. W. REUBEN WEBSTER (*presented in written form*).—The data presented in this paper represent a valuable contribution to the knowledge of internal strains produced in cold working metal. It cannot, however, be said to sustain the contention which the writer's paper[1] therein referred to was intended to controvert. The point under discussion was a statement in Mr. White's paper as follows: "It is likewise more desirable to reduce the thickness of the tube by many light drafts than by a few heavy ones. Such procedure guarantees more thorough and uniform kneading and interlocking of the crystal grains." No evidence of the presence of any such interlocking due either to light or heavy passes is to be found. It may be inferred from the facts presented that a multiple tube reduction of a given magnitude would be less likely to produce a condition conducive to season cracking than an equivalent single reduction. Such a demonstration, however, is of academic interest only, since good practice demands that a condenser tube be annealed as a final process to a degree sufficient to eliminate any internal strains due to drawing. Season cracking in tubes results from circumferential rather than longitudinal stresses.

Further, the magnitude of the reductions investigated by the authors is not comparable to those encountered in tube-drawing practice, wherein reductions of 30 to 40 per cent are

ordinarily made in one pass. It is also a common belief among tube makers that other considerations, such as the contour of the drawing die, have more effect in producing excessive internal strains than either the magnitude or number of reductions. Experiments are now being made to determine the magnitude and distribution of circumferential strains in tube drawing. The results are, however, not yet ready for presentation. **Mr. Webster.**

An attempt was made to reproduce the results reported in this paper on sheet brass, employing single and multiple reductions of 40 per cent, but the bowing effect due to unequal strains in the middle and side elements of the strips was much more pronounced than that due to strains in the exterior and interior elements. Further work in this direction is under way.

MR. R. L. TEMPLIN.—I should like to contribute some information in regard to rolling aluminum sheet. We have made a study of rolling practice in general, but our investigations are not yet ready for publication. We have found in connection with making aluminum sheet that for at least one stage in the process, we get a better sheet by making heavy reductions with a few passes than when we make lighter reductions with a larger number of passes. Rolling with a large number of light passes may be considered analagous, perhaps, to a riveting action; if heavy passes are taken, an upsetting action results: that is, the effect of cold working extends further into the sheet with a heavier pass than with a lighter pass. We also think that heavy passes tend toward a better homogeneity of the metal than a large number of light passes. **Mr. Templin.**

I notice the total range of reduction in the authors' experiments is but 17 per cent. If the diagrams had been plotted so as to give percentage of reduction instead of reduction in mills, they would probably have a more general application to rolling practice. Also the spring in inches is, to me, rather ambiguous, for while these strips were being rolled down their length was changing, and as I understand it, the spring is simply the distance between the two strips when their ends were placed together. It would have been more general to have given the radius of curvature.

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[1] "Light versus Heavy Reductions in Cold Working Brass," *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II (1917).

Mr. Templin. There is nothing said in the paper about the speed of rolling. We have found this to be an important factor in connection with aluminum, and I think that is also true for zinc. Nothing is said about the angle of approach, which probably could be figured from the data given; but it seems that with larger rolls the results would not be exactly as found from these miniature tests.

If one can use the increase in tensile strength of hard-worked or cold-rolled sheets as an indication of the effects of cold working, it is not difficult to draw up equations showing what may be expected from the cold working of sheet. Such equations for aluminum are very similar and differ essentially only in their constants, which in turn are governed by the particular alloy or constituents of the alloy.

Mr. Howe. MR. H. M. HOWE (*Author's closure by letter*).—I disclaim any intention of implying that the stresses are identical in two sheets rolled while superposed with those in a single rolled solid sheet, the thickness of which equals the sum of the thickness of the two superposed sheets. But it seems to me a fair assumption that the method used throws light on the question before the authors.

Simple as the principles seem, their application probably needs great discretion. Thus, in forging, a certain intermediate severity of pressure seems to cause the minimum of internal stress, while in an experiment which I will describe, the residual stress seems to decrease with the severity of the pressure, a course the opposite of that shown in the paper.

A too heavy blow of the hammer makes for cup-ending, a too light blow for egg-ending, for rather obvious reasons. The too light blow has a peaning effect. Its lightness tends to confine its effect unduly to the surface where it is delivered, and favors the spreading of that surface by the slightness of the friction between the tup and skin of the piece.

On the other hand, the great skin friction caused by a too heavy blow opposes the spreading of the skin, while its very momentum tends to exaggerate the movement of the deeper seated layers in comparison with the superficial ones.

A blow of intermediate severity leaves the end of the forging nearly flat, and thus would seem to leave the minimum of internal stress.

Mr. Howe.

A simple but instructive experiment, bearing on this subject, can be made with a pile of sheets of paper. Set half a ream of paper on your desk, with its six faces square and parallel. Now press very lightly on the top sheet with your thumb nail, drawing it gently to the right, repeatedly, say forty times. The lighter the pressure the more will the right hand travel of the top sheet outrun that of the underlying sheets, so that with a very light pressure, only a very few of the uppermost sheets slide to the right to any important degree. The pile forms a sharp overhanging cornice at its right. Again square your pile and now press down firmly on it with your palm, while moving it as before to the right. This time the right hand motion extends very much deeper into the pile, and the cornice at the right is much less pronounced.

The greater inequality of travel under the light pressure seems to teach that here light reductions, corresponding as they do to light pressure, should cause greater internal stress for given total reduction than heavy ones.

Here it is the friction between sheets that counts, while in forging it is the skin-friction between tup, anvil and forging.

This is one of the many illustrations of the difference in behavior between concrete and discrete masses.

Any value the paper may have seems to me in presenting a new mode of studying these questions.

ON THE SHATTERED ZONES IN CERTAIN STEEL RAILS, WITH NOTES ON THE INTERIOR ORIGIN OF TRANSVERSE FISSURES.

By James E. Howard.

Shattered Zones in Rails.

At the last annual meeting of the Society, Messrs. Waring and Hofammann presented a paper describing the shattered state of the metal which they had found in certain steel rails, in a steel tire and in a rolled steel wheel.[1] The character of the shattering cracks differed in the rails and the wheels in respect to their size and orientation. In the wheel and tire the cracks were longitudinal and radial; in the rails, they were oriented in different directions and were shorter. The characteristic differences in these dissimilar shapes suggested the thought that shape and dimensions of the members influenced the development of the interior cracks. Since the shattered metal occurred in members which had not been in service, the responsibility for their development was placed upon antecedent conditions of manufacture. Furthermore, since they occupied zones having definite relations to the shapes of the members, these facts carried with them the inference that their formation occurred within the limits of certain stages of fabrication. Promising directions in which inquiry might be continued were thus pointed out in the results which were presented by the authors.

Examination for Shattered Metal.—To ascertain whether a shattered state exists in a given case, the method of pickling in hot acid is one of the most expeditious. For a critical examination of the steel, the pickling should be of short duration or give way to some other method. A provisional method which has been used to advantage is to decarburize the steel. The metal having been planed off to the depth of the shattered zone and then decarburized, a thin layer of the surface metal is removed, whereupon the decarburized walls of the cracks are visible to

[1] E. M. Waring and K. E. Hofammann, "Deep Etchings of Rails and Forgings," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 182 (1919).

the unaided eye, picric acid having been used to bring about differentiation in color. The depths of individual cracks may be ascertained by this method, since decarburization takes place to the bottoms of the cracks.

Shattering cracks may be located by polishing only, without etching, although tincture of iodine or copper-ammonium chloride increases their visibility. The polishing is carried out with this particular object in view and not to produce the usual high polish for general metallographic purposes. The usual polishing for microscopic examination obscures these cracks—even those of considerable size—apparently by dragging the metal across them, since the cracks are without appreciable width of opening. No foreign inclusions have been found between their walls, so that a light etching conceivably might fail to locate such cracks.

These two methods, decarburizing and polishing without etching, we owe to Mr. R. H. Christ, Metallographist of the Bethlehem Steel Co.

The presence of a fine crack is often revealed by steel filings gathering at the crack. Fig. 1 shows the appearance of a rail section upon which fine dust from a hack saw gathered, the polarized particles forming a fringe one inch long in places. This rail section furnishes an extreme example of its kind. Under careful manipulation in draw-filing, fine steel dust may be arrested and disclose the presence of a fine crack. There is comparatively little trouble in locating them once the knack is acquired.

It appears to have been conclusively established that no inclusion exists between the walls of these cracks, while it was early shown that they existed in the steel before being subjected to any of the exigencies of service. The questions are: When do these shattering cracks have their origin; what are the temperatures involved, since they now appear as thermal effects; and what is the influence of chemical composition and the shapes and dimensions of the members displaying these cracks?

Origin of Shattering Cracks.—In steel rails the zones in which the cracks appear are located along the middle of the interior of the head and at the junction of the web and base. (See Fig. 6.) Those in the base have attracted little or no attention,

since base failures of rails have not been associated with these cracks. Fig. 2 depicts the shattered zones in a rail. The upper figure represents a horizontal, longitudinal surface along the middle of the head; the lower figure is a vertical, longitudinal section through the head, web and base. The shattered metal constitutes an interior zone in each case. A wall of considerable thickness encloses each zone. It may be remarked that the

FIG. 1.—Magnetized Steel Saw Dust on Rail Cut Apart with a Hack Saw.

shattered zones have been found to terminate before reaching the hot-sawed ends of the rails, with substantially the same thickness of walls of sound metal covering the hot-sawed ends as that of the peripheral shell. This being the case, it would be expected that sound metal would be found anywhere along the length of the rail, provided it had been hot-sawed at that place. If these observations are confirmed it is established

that shattering is a thermal effect; furthermore, that the time of occurrence is after the last pass in the rail mill; still further, that a relation exists between shattering cracks and mass of

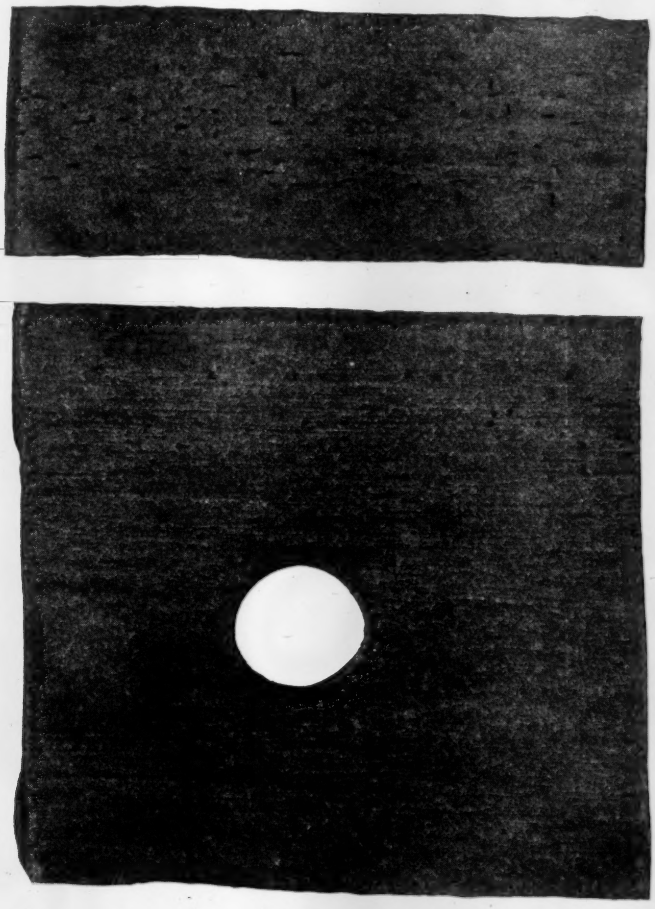


FIG. 2.—Shattered Zones in Head and Base of Rail. Upper Figure Represents a Longitudinal Horizontal Section along Middle of Head. Lower Figure, a Vertical Section through Middle of Head, Web and Base. Appearance of Surfaces after Pickling in Hot Hydrochloric Acid.

the member. So many convenient opportunities present themselves to confirm or refute these speculations that their status

should soon be known, and if not substantiated, the real causes ascertained.

Temperature Range in Which Cracks May Form.—Steel at rolling and forging temperatures has very little tensile strength. It has plastic resistance, depending in amount upon the rate of reduction in the rolls; no grade, however, has more than a few thousand pounds per square inch tensile strength at these high temperatures. In view of the reduced tensile strength of the steel at plastic temperatures, even with a decided reduction in the value of the modulus of elasticity, there seems to be opportunity for severe shrinkage strains to be set up in cooling. Such strains have been measured on so many occasions that there is no doubt of their existence. Simultaneous orthogonal strains in three directions are necessarily set up when steel cools, in different degrees according to the conditions of cooling. As pointed out in the discussion of Messrs. Waring and Hofammann's paper, there seems no inconsistency in believing that brittleness may be displayed by hot as well as by cold steel, through the action of these simultaneous strains in three directions.

Internal strains result from differences in temperature prevailing at some period in cooling. This would seem to explain the presence of shattered zones in the head of the rail and at the junction of the web and base, since it is at these places that differences in temperature between the exterior and interior metal might exist. If there is a substantial basis for these remarks, it would follow that the heavier sections would be more apt to display shattered metal than the lighter ones. Forgings should be similarly affected, depending upon their size and rate of cooling. Rapid cooling or quenching introduces a different set of conditions. By means of sudden quenching, steel may be ruptured from the exterior, or exfoliation may take place. Fig. 3 illustrates the exfoliation which took place in the head of a rail which was heated and quenched.

Effect of Chemical Composition.—The rails which have been found to have shattered interiors would be classified as hard rails. Certain of the properties of steel vary with its carbon content. Hard steels have a different specific gravity from soft steels. They also have different coefficients of expansion, and after heating and quenching they show differences in respect

to restoration of dimensions when subsequently raised to moderate temperatures. The greater sensitiveness of hard steels compared with medium and soft steels in respect to heat treatment is known to all steel workers, although the reasons remain to be determined. It is therefore desirable to ascertain whether the influence of chemical composition is a vital consideration. Differences in the density of steel are found in different grades of metal in their annealed state and further differences are shown after they have been heated and quenched. These changes in density may be significant. Another important question is the ability of the different micro-constituents to accommodate themselves to strains of tension in the interior of

FIG. 3.—Exfoliation of Head of Rail from Heating and Quenching. Only Peripheral Surface Exposed to Quenching Medium.

the mass of the steel during the period of cooling, where the phenomenon of permanent set cannot take place by reason of the action of simultaneous orthogonal strains in three directions.

Shattered zones have not been reported in the milder grades of steel. It is against the judgment of steel makers to roll very hard steel rails, and in the opinion of the writer it is preferable to choose the milder grades of steel for general purposes when they are suitable, rather than the harder grades; being fully aware of the relations, however, shown by the hard and soft steels in their primitive tests. Specifications governing the acceptance of steel call for properties which are not made use of in service, and the relations of these properties to the endurance of the steel under service conditions are seldom known with

accuracy. Cumulative data are being acquired on the relation of chemical hardness to shattered zones in rails, in the endeavor to advance this branch of the subject having to do with the proper use of materials.

It has long been a matter of record that certain changes in the properties of metals occur after the lapse of time, and that overstraining forces encounter different degrees of resistance at different times. In the experimental introduction of thermal cracks, a sensitiveness of behavior is witnessed in steel rails when first cooled which is not experienced under similar treatment when reheated. To Mr. Christ we are indebted for observations of this nature.

The presence of shattered zones in steel rails is not a matter peculiar to rails of recent rolling. Cracks in steel tires, the descriptions of which seem to identify them as belonging to the class of cracks illustrated by Messrs. Waring and Hofammann, appear to have been encountered in the re-turning of tires in locomotive shops. According to testimony received, such tires were welded or rather fused with an acetylene torch, after which they were returned to service. Shattered zones in the heads of steel rails also appear to have been found at an earlier date but were disregarded, or perhaps attributed to rolling green steel.

Summary.—Progress in the study of shattered metal and its present status so far as it has come to the knowledge of the writer may be summed up as follows: Shattered zones are interior manifestations, being surrounded with walls of unshattered metal. The shattering cracks in rails are located along the middle of the head and at the junction of the web and base. The cracks themselves are of appreciable size in two directions but in their third dimension are very minute. The minimum distance separating their walls is probably much less than 0.00002 in. No foreign inclusion is contained in the cracks. They both follow grain boundaries and pass through the grains of the steel. They are not associated with other structural defects, nor peculiar to segregated areas, except in so far as they are prevalent in the harder grades of steel. The softer grades of steel so far as present observations have covered the subject are free from shattered metal. The shattering cracks appear to be of thermal origin; that is, they are cooling or shrinkage

cracks. They are acquired presumably after the last pass in the rail mill. The hot-sawed ends of rails have been found unshattered. The cracks occupy zones in the section of the rails which upon cooling acquire a state of initial tension, and have not been found in those parts which are left in a final state of compression. Experimental treatment has shown a susceptibility to display similar cracks in rails direct from the hot saw, not displayed when reheated after cooling. In steel tires, the disposition, size and orientation of the cracks are even more suggestive of a thermal origin than those in rails.

TRANSVERSE FISSURES.

Messrs. Waring and Hofammann in their paper associated the display of transverse fissures with shattered metal in the heads of the rails. Investigations show transverse fissures in rails both with and without shattered heads, as well as rails with shattered heads but without transverse fissures. In considering the subject of transverse fissures, some confusion has arisen through failure to discriminate between the physical features which lead to the formation of fractures having interior origins, and structural or chemical causes which make stronger or weaker rails—two distinct questions.

In the first published report by the Interstate Commerce Commission on transverse fissures, relating to an accident which occurred in 1911, the writer believed that he explained why this type of fracture developed, ascribing the cause of "the internal fissures . . . to the introduction of internal strains" resulting from the wheel pressures. This explanation was regarded almost or quite self-evident. The tensile fracture of a bent beam is ordinarily expected to have its origin in the fibers most remote from the neutral axis. The introduction of internal strains of compression in the head of the rail next to the running surface removed the opportunity of a fracture having an exterior origin and located the danger zone in the interior of the head. This explanation was not based upon any peculiar condition which prevailed in the particular rail which then failed, but upon a law of mechanics. It is obvious that no member or portion of a member which is in a state of internal compression can contain the origin of a tensile fracture. That constitutes the

crux of the explanation of the interior origin of a transverse fissure. The wheel pressures are responsible for the introduction of the internal strains of compression, in excess of those incident to the cooling of the rail at time of fabrication. There is no remedy against the introduction of these internal strains in rails when they are put into service.

Quoting from a current report of the Bureau of Safety of the Interstate Commerce Commission on an accident attended with loss of life caused by a transverse fissured rail: "It is important to consider whether there are any means of escape from the tendencies which lead to the formation of transverse fissures. In respect to the cold-rolling action of the wheels there are none. The utmost which may be accomplished is to preserve a relation between the ability of the steel to endure these unavoidable strains and the service conditions which are responsible for them, to the end that the ultimate endurance shall not be reached while the rail is in the track. . . . Rails cannot be included in the group of engineering structures which are classified as permanent ones. It is the method of carrying loads upon wheels, the very essence of land transportation, which excludes rails from the group of permanent structures."

The introduction of remedial measures or the adoption of means for eliminating rail failures is retarded so long as confusion exists respecting the basic causes of rail failures. More than a score of explanations have been offered for the formation of transverse fissures. Some of the explanations have referred to features which have an influence upon the primitive properties of the steel; others have been advanced which bear no relation to the original properties or service conditions. Rail failure statistics, for the five-year period ending in 1918, number about 21,000 rail failures, representing not all of the railroads of the country, nor all of the rail failures on the roads which are reported. In a ten-year period the number of failed rails reported exceeded 50,000. As in the practice of medicine, a case must be correctly diagnosed in order to prescribe the proper treatment. But in these instances the failures, as they appear in the published statistics, were not diagnosed. So many cases only were reported, said to be located in certain portions of the individual rails, or even less explicitly designated merely as "broken rails." This

is not a matter mentioned in the spirit of adverse criticism but in one of regret, since it is felt that the best use of existing opportunities is not being made.

Returning to the explanation of the interior origin of transverse fissures, Fig. 4 is introduced to illustrate the appearance of a fracture of this type. In the different stages of development they are found in all sizes. They are commonly located

FIG. 4.—Transverse Fissure in the Head of a 100-lb. Rail.

on the gage side of the head or over the web. Among 663 fissures which occurred on one railroad, 535 occurred on the gage side of the head, 128 over the web, and none on the outside of the head.

Fig. 5 represents a hypothetical beam, the upper shaded zone of which is assumed to be held in a state of initial compression by an external force. Detached and unrestrained, it would assume the dotted length. The failure of this hypothetical

beam under repeated bending stresses, if it occurred on that side, would be expected to take place below the zone of initial compression, that is at an interior element. Were the zone of metal in compression not maintained in that state by an external force, then its reaction would put strains of tension in the interior metal, augmenting those due to the direct bending stresses applied to the beam, increasing the intensity of the latter. The influence of the metal in compression in a rail is not confined to any one part of its length, but extends along the entire top of the head from one end to the other. Its influence in promoting rupture will be felt in all parts of the length of the rail. A transverse fissure has been found $1\frac{1}{8}$ in. from the end of the rail, a location where internal strains were not only the dominant ones but practically the only ones present.

The extent to which these internal strains are realized in rails which have been in service is illustrated in Fig. 6. Internal

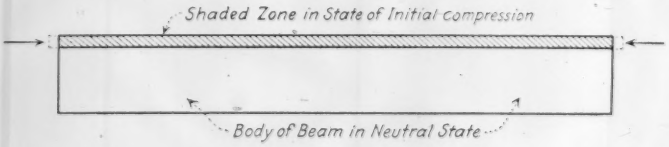


FIG. 5.—Hypothetical Beam, Upper Zone Assumed to be in a State of Initial Compression, Body of Beam in a Neutral State.

stresses of compression amounting to 20,000 lb. per sq. in. are not infrequently found in the upper part of the heads of rails which have been in service, together with a state of tension in the interior of the head ranging from 5000 to 8000 lb. per sq. in. They are chiefly due to the cold-rolling action of the wheels on the heads of the rails. Cooling strains of fabrication are of lesser degree.

The measured strains which Fig. 6 illustrates, converted into corresponding stresses, are conservative rather than maximum values. They represent average values distributed over the length of the rail, measured on strips in which the strains vary at different depths of cross-section. It is clear that a wedge action of the metal adjacent to the running surface must be exerted upon the metal next below, taking place along the entire

length of the rail. This action seems adequate to account for the presence of incipient transverse fissures which are frequently found at short intervals along the length of the rail. In fact, well-advanced transverse fissures have been found in close proximity to each other, in some cases barely an inch apart, a

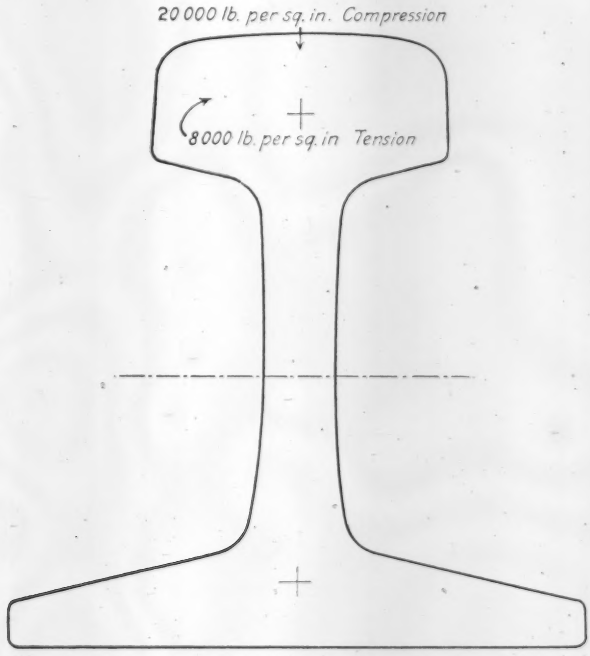


FIG. 6.—Internal Stresses in Head of Rail Caused by Wheel Loads. Zone Immediately below the Running Surface of the Head in Compression, Interior of the Head in Tension. (Crosses Indicate Usual Location of Shattered Zones.)

development which could not take place as the result of bending stresses alone.

Tensile stresses, the direct result of wheel loads in the track, have lower values in the head than in the base of the rail. Such were the results found in the track by measurements made by the writer in 1893 and subsequent years, and since then con-

firmed by other observers. The most recent track measurements, made under modern equipment, show fiber stresses which seem inadequate in magnitude and number of repetitions to account for the rupture of rails, considering bending stresses alone. The fiber stresses in tension being greater in the base than in the head, bending stresses alone should result in base fractures rather than fractures in the head. In the flanges there are compensating features since the cooling strains there are compressive. Along the middle of the base, tensile strains are commonly present, and while compressive strains in the upper part of the head tend to relieve that portion from danger of rupture, in the base strains of tension should increase that tendency. As a matter of fact, rail failures from longitudinal tension having their origin in the base have not been witnessed by the writer. Base fractures are numerous but they originate usually at surface seaminess. A longitudinal crack first forms, which may result in a crescent-shape fracture only, or may culminate in a fracture extending in three directions from the initial longitudinal crack, separating both flanges and followed by an extension upward through the web and the head, thus completing the rupture of the entire rail. The certainty with which the directions of these lines of rupture usually may be traced leaves no doubt as to the manner of failure.

Why fractures develop with interior origins; why the type of fracture witnessed in transverse fissures occurs, is explained as above by a law of mechanics. Why one rail fails earlier than another, or why a rail endures certain traffic conditions and weights of equipment and fails under other and heavier equipment or more severe service conditions, is quite another question.

Efforts to prolong the lives of rails have been carried out in two directions: namely, increasing the chemical hardness of the steel, and increasing the cross-section of the rails. Immunity against rupture has not been attained by either method. The failure of rails goes on conspicuously on trunk lines where tonnage is greatest. There are other railroads which seldom have rail failures. The problem is not to produce a rail which will successfully meet traffic conditions on some railroads only, but to produce one which will retain a margin in safety on all,

including those roads where present traffic conditions are most severe. The expression "retain a margin in safety" is here used. Primitive strength is not the sole consideration. That alone may be attained. The real problem is one of endurance against track conditions and stresses without serious impairment of physical properties—to produce a rail which will not be dangerously affected during its term of service in the track whether that term be of long or short duration.

Since the days of wrought-iron rails and the introduction of steel rails there has been a gradual increase in chemical hardness of the metal, which has resulted in rails containing as high as one per cent of carbon. Other hardeners have also been used. Rails of great chemical hardness have the advantage of greater resistance to abrasion and wear. But, referring to Fig. 4, it will be seen that this transverse fissured rail shows no appreciable wear nor change in shape, yet it developed this dangerous type of fracture. Hard rails, therefore, are not immune from transverse fissures. The fact that they retain their shape substantially with slight wear is perhaps a leading circumstance in the development of transverse fissures. In such rails the interior tensile strains are not migratory. The elements most strained remain as such, whereas loss of metal by abrasion would shift the positions and relations of the internal strains, relieving some portions and increasing the strains in others. The rupture of a rail presents an analogy to the breaking of a piece of wire by repeated bending: it is a loss of effort to bend it a number of times in one place and then begin anew in another place. Forged and rolled steel wheels and tires are exposed to the same cold-rolling conditions as rails. A 36-in. steel tire, removed from its plates, sprung together $\frac{15}{16}$ in. when cut apart radially, indicating the relief of internal strains of compression in the metal adjacent to the tread.

No high-carbon-steel rails have resisted the introduction of internal strains from the cold-rolling action of the wheels. Such strains are the result of local stresses which exceed the elastic limit of the metal, whence it follows that all rails in service represent metal which has been strained beyond its elastic limit in some part of its cross-section. Manganese-steel rails eventually succumb to the cold-rolling action of the wheels. The tough-

ness of the metal at the running surface of the head is destroyed, and rupture takes place by the development of crosswise fractures. Unlike transverse fissures in carbon-steel rails, the crosswise fractures in manganese-steel rails have exterior origins. They begin at the running surface of the head, then progressively extend downward through the head, and into the web. It is a peculiarity of manganese steel that toughness is retained in the remaining unruptured portion of the rail; the reverse is true of carbon-steel rails.

The discovery of shattered metal in many rails which displayed transverse fissures gave encouragement for a time that a structural defect had been found, the elimination of which would restore the inherent ability of the rail to endure service stresses with a margin of safety. Not that the elimination of this or any structural defect would render the steel unbreakable, but it would effect such an improvement in resistance that rails would sustain present wheel loads without failure by the development of transverse fissures. The zone of shattered metal which is located in the head of the rail includes the location of the nuclei of transverse fissures. It was therefore quite natural to infer that the elimination of this shattered zone would at least prolong the life of the rail, if indeed it did not completely arrest development of transverse fissures.

In a degree these hopes may be realized. Time and the acquisition of more complete data are required to complete the demonstration. It will be necessary to effect the elimination of the shattered zones and furnish assurance that such elimination has been accomplished, followed by track experience with structurally unshattered rails. If certain grades of steel are found to be susceptible to shattering and other grades are not, an inherent and practically unavoidable tendency being present, such steels may not be used, if shattering is a fatal defect.

At present so vague and indeterminate is the information on the subject that it is not certain whether the presence of shattered metal accelerates or retards the formation of transverse fissures. If transverse fissures were found only in rails with shattered interiors, then it would logically be expected that the elimination of the shattered zones would result in the elimination of transverse fissures. But such is not the case. Transverse fissures have

developed in rails in which no structural defect has been found. Whether the presence of a shattered zone retards the formation of a transverse fissure rests upon the uncertainty as to whether a diffusive action takes place within the shattered zone, relieving the intensity of the internal strains transmitted to the interior metal from the cold-rolled running surface of the rail, affording opportunities for relief, instead of by the development of intermittent incipient fissures. The depth and strength of the surrounding shell of intact metal are important factors. In this, as in other cases, the line of reasoning ultimately reverts to wheel pressures,—having reference to the intensity of the impinging pressures and the volumes of metal disturbed and put into states of compression and tension respectively.

The desirability of acquiring more complete data upon the subject of shattered metal admits of no question. It is a feature seemingly associated with the composition of the metal as well as with the treatment of forgings and rolled shapes. It is not regarded as a matter peculiar to rails, bearing specifically only upon the development of transverse fissures. Certain forging and rolling operations result in the formation of interior cavities in sound steel. The formation of the threaded sections on track bolts furnishes illustrations of the introduction of interior cavities in the shanks of the bolts when the threaded sections are formed between rectilinear dies. The shattered zones in the heads and bases of certain steel rails present themselves as incidents associated with general matters connected with the uses of steel.

DISCUSSION.

Mr. Comstock.

MR. G. F. COMSTOCK (*presented in written form*).—This paper is undoubtedly of great interest to all who study the problems connected with rail failures, but it would be more valuable if actual results of individual experiments were given, instead of merely the conclusions of the author. For instance, it would be interesting to know in just how many cases the "shattered condition" was found to stop before reaching the hot-sawed end of a rail, because the author himself seems to feel the need for confirming this observation. Also, an intelligent appraisal of the value of the author's conclusions would seem to require a knowledge of what proportion of the "shattered zones" he observed were identified only by the pickling method with strong hot acid. As pointed out in the discussion of Messrs. Waring and Hofammann's paper last year, this method will produce fissures or pits in strained or segregated steel, and the marks in Fig. 2 resemble very closely the pits due to etching of fine sulfide streaks. The zones in which these streaks are found are always enclosed by "walls of sound metal of considerable thickness", just as noted by the author.

The production of exfoliation by quenching, as illustrated in Fig. 3, is interesting, but the illustration shows a rail that has been in service, and it is not stated that this phenomenon was also met in new rails. If new rails are also exfoliated by quenching, this fact cannot be held to support the theory of thermal origin of the shattering cracks. In suggesting the decarbonizing method for showing the "shattered condition," the author must feel that slow cooling from the decarbonizing temperature does not cause the internal cracks which are being sought; he states, however, that rapid cooling causes "rupture from the exterior, or exfoliation." Why then should an intermediate rate of cooling produce an entirely different kind of cracking? The author's paper does not explain this difficulty into which his assumptions and reasoning lead.

Another point on which more information from the author would be very desirable, is in regard to the frequency with which

the shattered condition is met in new rails; what proportion of the new rails examined showed shattered interiors, and why do not nearly all of them show this defect if it is merely a question of thermal effects? **Mr. Comstock.**

The author's discussion of transverse fissures is as usual reasonable and clear, but his hesitancy in accepting the identity of their nuclei with the transverse cracks of the "shattered zones" seems hardly justified. The presence of a transverse fissure in a rail might reasonably be regarded as evidence of at least one "shattering crack" in that rail at the nucleus of the fissure, even if others could not be found near it by etching or other metallographic methods.

A question in regard to transverse fissures which the author does not elucidate is the occurrence of them so largely in certain heats or rollings of steel. Metallographic investigations should throw some light on this point, as there must be a reason for the greater susceptibility of those heats to this kind of failure. It is unfortunate that the present paper does not report any work done along this line, which appears to offer the best chance of finding some definite remedy for the "shattered state of the metal" and for transverse fissures.

MR. HENRY S. RAWDON (*presented in written form*).—In the study of internal defects of any kind in metals it is always essential that they be examined in their initial condition; particularly is it desirable, in the case of fractures, that the face of the break be examined before it has been attacked in any way by etching reagents, submitted to oxidation or other changes accompanying heating or in any way treated so that its characteristic features are changed, and thus a certain degree of uncertainty introduced. The method of decarburization described by Mr. Howard, in the opinion of the writer, has the same disadvantage that location of the defects by deep-etching has, that is, the defect after it has been located cannot be examined in its initial and unchanged condition. Besides, the method is rather time-consuming in its operation. It is believed the procedure described by the writer for the location and study of defects of this kind[1] is free from **Mr. Rawdon.**

[1] Henry S. Rawdon and S. Epstein, "Metallographic Features Revealed by the Deep Etching of Steel," *Technologic Paper No. 156*, U. S. Bureau of Standards, and Henry S. Rawdon, "The Nature of the Defects Revealed by the Deep Etching of Transversely Fissured Rails," *Report No. 85 to Rail Committee*, American Railroad Association.

Mr. Rawdon. this criticism, in that it is much simpler in application and the metal is not changed in any way. This method is based upon the principle briefly referred to by the author in the use of steel filings upon a magnetized specimen. The section for examination should be polished as for microscopic examination, magnetized, and then bathed in a light oil in which very fine iron dust is in suspension. Kerosene is very suitable as a liquid and the "mud" from cast-iron lapping disks answers admirably for the iron dust. The specimen is finally washed in clear kerosene, care being taken that the polished face of the specimen is not touched. No particular skill of manipulation is required for carrying out the operation.

It is shown by the writer in the publications referred to above how, after the defects are located by the method described, their positions may be permanently marked by a punch mark at each end of the "crack". The specimen may then be cut into pieces of suitable size and each broken by a transverse bend along the line of the located defect. It is also possible by rather deep punch marks to open up the metal along the line of the defect before the specimen is broken. In every case which has come under the observation of the writer the face of the internal fracture revealed after breaking the specimen at the spot where the defect was located was identical in appearance with that of the usual "nucleus" of a transverse fissure. It is believed that the method can be used to advantage to throw further light on the probability of such an internal fracture serving as the "nucleus" or starting point for the development of a transverse fissure. If, in the examination of a used rail showing an internal zone of shattered metal, regardless of whether such a rail had developed in service transverse fissures or not, it is found upon examining the faces of the internal fractures located and revealed as explained above that some of them are associated with areas, large or small, having the smooth silvery appearance which is characteristic of the greater portion of a transverse fissure, one would be justified to some extent at least, in concluding that the bright silvery area represents a "detailed fracture" starting from the edge of an internal fissure of the shattered zone and that in time if the same conditions had prevailed it would have grown into a "true" transverse fissure.

Mr. Rawdon.

In short, if all incipient transverse fissures, even in their very earliest stages, are associated with a "nucleus" which is identical in its characteristics with the internal fractures of "shattered steel," one is lead inevitably to the conclusion that the "nucleus" existed as a discontinuity in the metal before the growth of the "fissure" began.

In regard to the statement by the author that "there seems to be no inconsistency in believing that brittleness may be displayed by hot as well as by cold steel through the action of . . . strains," it would appear to the writer that such brittleness ought to reveal itself, if the metal is tested while hot, in a suitable manner. Brittleness in hot steel is usually associated with such a phenomenon as red-shortness due to a high sulfur content, to certain addition elements which form a eutectic solidifying at a fairly low temperature,—boron steel is an excellent example,—etc. The brittleness referred to here, however, is of a different type and is supposed to occur in normal steel. If steel is brittle at any stage during its heating or cooling, this property should be revealed by a suitable method of testing, preferably some form of the notched-bar impact test being used. Data along this line are rather rare. The most recent and comprehensive study is that of Reinhold.[1] The results of this investigation are in close agreement also with those obtained earlier by Guillet and Revillon and by Goerens and Hartel, references to which are included in the above article. In Fig. 1 is shown in graphical form the characteristic behavior of a steel of 0.40 per cent carbon content when tested at different temperatures by means of the notched-bar impact test. Although the steel used is not of the composition in current American use for rails, the form of the curve is characteristic of steel of such composition as is shown by the work of Goerens and Hartel in which 0.8-per-cent carbon steel was used. The average approximate temperature of rails when they reach the hot saw is slightly above 900° C. (1650° F.).[2] The data given in Fig. 1 for the notched-bar impact test cover then the entire temperature range of the cooling rail as it leaves the hot saw. A word of explanation is necessary: all bars tested

[1] O. Reinhold, "Über mechanische Eigenschaften von Flusseisen bei verschiedenen Temperaturen," *Ferrum*, Vol. 7, pp. 97, 113 and 129 (1916).

[2] Burgess, Crown, Rawdon, and Waltenberg, "Observations on Finishing Temperatures and Properties of Rails," *Technologic Paper No. 38*, Bureau of Standards, p. 17.

Mr. Rawdon. at a temperature below 525° C. (approximate) are stated to have broken under impact; those tested above this temperature bent and tore partially in two, but no breaks were produced as at the lower temperatures. As stated by Mr. Howard, the tensile strength of steel is reduced very materially at high temperatures; this is shown in Fig. 1. There is, however, no evidence of brittleness in the material in the range of temperature in which it begins

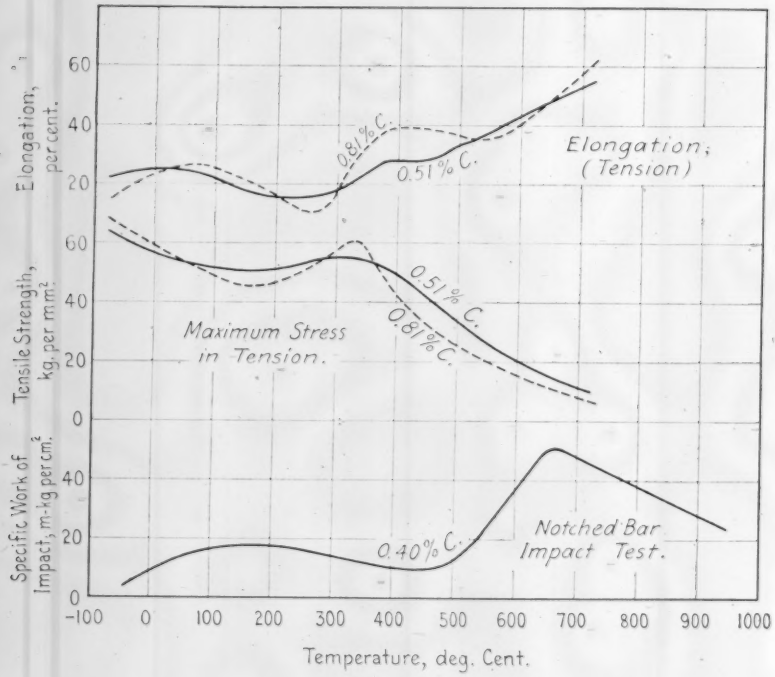


FIG. 1.

to become plastic. Although the resistance to impact drops materially if the temperature is increased, as is naturally to be expected, the "impact value" obtained at 900° C. is considerably greater than that for the same material at ordinary temperatures. The low "impact value" of the steel in the neighborhood of 500° C. (930° F.) is, however, very striking and it appears to the writer that the properties of the material at this approximate temperature are very significant with respect to the behavior of

the metal when cooling after rolling. It would be expected from the plotted data that the material at this stage is quite sensitive to rough treatment, in that the tensile strength is still very much below that shown by the steel at ordinary temperatures and its dynamic properties, as shown by its resistance to shock, are at a minimum. The suggestion is offered that the study of the available data of this kind should be of material assistance in predicting the probable behavior of steel rails, forgings, etc., upon cooling. **Mr. Rawdon.**

The suggestion offered by Mr. Howard that the internal shattering within the rail occurs after the material leaves the hot saw has necessarily been assumed as a basis for the above discussion.

It is not clear to the writer how the author reconciles the idea expressed as to the possible retarding action of an internal zone of shattered metal upon the formation of transverse fissures "by a diffusive action . . . within the shattered zone, relieving the intensity of the internal strains," with the statement that "well-advanced transverse fissures have been found in close proximity to each other, in some cases barely an inch apart." It would seem logical to infer that if several *incipient* transverse fissures form in close proximity to each other, "diffusive action" referred to should be sufficient to prevent further development so that *well-developed* transverse fissures ought never to occur in close proximity to one another.

MR. ROBERT JOB.—The results obtained by Messrs. Waring and Hofammann, to which Mr. Howard has referred, in connection with shattered zones, are of very great interest, and the results of the investigations during the past year by the American Railway Engineering Association and others also have been. It is true that no direct connection has been established, as yet, between the shattered zones and transverse fissures, but a good deal of information has been obtained during the past few years, particularly in connection with transverse fissures. As an example, we may say that to-day we know that transverse fissures occur in rails throughout the entire range of composition, beginning with 0.20-per-cent carbon steel, and also that fissures are found under varying conditions of wheel pressures, running from the usual American practice to that abroad, where generally **Mr. Job.**

Mr. Job. lighter wheel pressures are prevalent. In the case of fissures which form in 0.20-per-cent carbon steel—the lower range of carbons—we have been told by those who have used the rails that these fissures occurred only when the steel was unsound.

Mr. Howard mentions in his paper that efforts have been made in two directions to prolong the life of rails, which he names. To these might be added efforts that have been made to detect and keep from service the occasional brittle rail which is likely to cause damage in service and in which fissures are likely to result. Under the system of tests which is usual at the present time, in which three rails from a heat are tested and all the rails represented are either accepted or rejected, there is—as all of us know who have made a test of this in mill work—a great possibility of not only accepting defective, brittle and unsound steel, but also of rejecting sound and serviceable steel which would be very good to use; and there is no question in my own mind after extensive trial of the system, but that the test of a rail from each ingot—as we have taken occasion to mention from time to time—is of very great help in weeding out occasional brittle and unsafe rails.

There is another point we might mention in connection with the general situation. I do not wish to cast any aspersions upon any one branch of manufacturing as compared with another, but when we go over the list of improvements which have been made in practical lines of industry for the past decade and even in the past five years, and see the increased service and serviceability which has been obtained as a result of the study of the properties of materials, it makes us realize in following up the work which has been done in connection with rails, that practically no change or very little change has been made in their manufacture toward the betterment of the product, apart from such changes as were made with the object of increasing the tonnage capacity of the mill; as, for instance, in the reheating of blooms. We quite realize the advantage which is derived from the reheating of blooms, but, practically, it is pretty much a question of tonnage, and is of direct benefit to the mill although it is also a benefit to the consumer. I believe myself that if a critical, constructive study by the mills of the causes underlying and resulting in rail failures were made, it would be of direct

practical value, not only to the traveling public, but also to every mill which proved by its work the desire and effort to better the quality of its product. Mr. Job.

MR. M. H. WICKHORST.—The literature of the subject of transverse fissures begins with Mr. Howard's report of the Manchester, N. Y., wreck in 1911 (at which time the term was first used), and the subject has been under active investigation since. At first, all the usual methods of testing steel were used in the investigations, but for a number of years the results were of a negative character, resulting in a process of elimination. Chemically most of the rails met the usual requirements, although most of them were up toward the upper limit for carbon or exceeded it. The microscope did not disclose any peculiarities of structure. Longitudinal tension tests showed that the tensile properties were normal in the metal in all parts of the rail section, except in the interior of the head, where the ductility was low. Mr. Wickhorst.

It had been noticed that the simple transverse fissure always developed from a granular spot or "nucleus" in the interior of the rail head. It was a natural thought that the nucleus was a crack from which the fissure developed and the condition of low ductility in the interior of the rail head suggested that there was a generally ruptured or shattered condition of the steel in this location. Examinations of sections along different planes by high polishing, particularly after slight etching, disclosed interior cracks to a slight extent, but it remained for the deep etching work of Messrs. Waring and Hofammann, as described before this Society last year, to disclose the very numerous shattering cracks existent in the interior of the rail head. The question was then raised whether the etching cracks were not a result of the deep etching process rather than due to a condition of the steel, but the work of Rawdon at the Bureau of Standards showed that the cracks are pre-existent, that is, they are present previous to the etching, the acid serving to open them up.

We may say that fissures of the simple transverse types are developments of cracks in the rail head, but the question still remains as to the origin of the cracks. As pointed out by Mr. Howard, it has been found that the zone of shattered steel in the interior does not extend to the end of the rail as cut by the hot-saws, but terminates about one-half inch away from it, indicating

Mr. Wickhorst. that it was not in the hot bar as it left the finishing rolls but developed during or after the cooling. In other words, the cracks seem to be shrinkage checks.

We may view with satisfaction the progress that has been made in recent years in our knowledge concerning fissured rails and we may further hope by continued diligent research to effect, in time, a remedy for, or at least a considerable mitigation of, this treacherous type of rail failure, in which breakage is apt to occur with little or no previous surface indication.

Mr. Howard. MR. J. E. HOWARD (*Author's closure by letter*).—Concerning shattered zones in steel rails, Messrs. Waring and Hofammann at the outset announced that such zones were present in new rails. The results of their observations were early confirmed. Localized as they were in the head and at the junction of the web and base, together with the fact that the lines of separation passed uninterruptedly through the metal, no doubt remained that the shattered lines were incipient cracks in the steel. Pickling merely afforded a convenient means of showing their presence. Mr. Christ, metallographist of the Bethlehem Steel Co., has shown how the cracks may be readily located by less drastic polishing than usually given steel surfaces for microscopic examination. Minute cracks in steel are frequently found by careful draw-filing—a well-known shop expedient—polarized filings being arrested at the cracks.

In the early observations which followed the announcement of Messrs. Waring and Hofammann of the presence of shattered zones in certain rails and also in steel tires, it was noted that the shattered zones in rails did not extend to their hot-sawed ends. This circumstance fixed the time of their formation as occurring after the last pass in the rail mill, also appearing to establish the shattering lines as shrinkage cracks.

These few remarks, it is believed, enumerate such advance as has been made in the examination of shattered zones.

The probable brittleness of steel at high temperatures referred to by the author, as stated, contemplated simultaneous strains in three directions.

The presence of shattered zones has not been found in all grades of steel, nor in all weights of rails. All are exposed to shrinkage conditions, whence it would appear that certain grades

of steel endured such strains without rupture, while other grades yielded by fracture, resulting in shattered zones in such parts of the rail where conditions suitable therefor existed. Mr. Howard.

No chemical nor structural defect seems associated with the shattering cracks. Transverse fissures occur in rails with shattered zones, and they occur also in rails which do not display such zones. Information upon the influence of shattered zones on the development of transverse fissures must come from carefully compiled track records of the rails.

EFFECT OF MACHINING AND OF CROSS-SECTION ON THE TENSILE PROPERTIES OF MALLEABLE CAST IRON.

By H. A. Schwartz.

Introduction.

There is a wide-spread though not necessarily correct belief that machining greatly weakens malleable cast iron. In justice to the engineer, who as a basis of design must know how nearly the specified properties may be attained in the sections he proposes to use, the reasons for this belief should be investigated. If the belief is ungrounded, it should be discredited; if it is well founded, the necessary data to prove it such should be available. Accordingly the experiments forming the basis of this paper were undertaken. In a discussion of the author's paper,[1] Bean submitted data on the relative strength of the center and surface of large castings and of machined versus rough test specimens. The additional object of these experiments was the securing of further data to substantiate any conclusions that may have been reached at that time.

When specimens of malleable cast iron of various cross-sectional areas, including both machined and unmachined specimens, are tested, a number of variable factors may influence the physical properties. For convenience in referring to these variables in the paper, they are listed and numbered below:

1. Decarbonization may strengthen the surface metal.

2. The surface metal may be stronger than that at the center, due to the effect on the grain structure of the rate of cooling in freezing.

3. Specimens of small cross-sectional area as cast may be relatively stronger from the same cause.

4. Slower cooling in the larger cross-sections may precipitate primary graphite with disastrous results.

5. The larger cross-sections may not be mechanically sound

[1] "Some Physical Properties of American Malleable Cast Iron," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

due to shrinkage. This weakens them as a whole and also weakens the center as compared with the surface.

6. The machined specimen, owing to its uniformity of cross-section, will yield apparently better results, particularly as to elongation and reduction of area, than a rough one.

A course of experiments was planned which should permit of comparisons between specimens as nearly similar in respect to five of these factors as possible in order to test the effect of the remaining variable.

PREPARATION OF SPECIMENS.

It was evident early in the investigation that variable No. 5 would cause prohibitive difficulty in specimens geometrically similar to the A.S.T.M. specimen.[1] Although this particular specimen is quite satisfactory in the size called for in the specifications, in sizes much larger or much smaller, as would be the case in the wide range covered in this investigation, specimens geometrically similar would not be satisfactory. Preliminary experiments were therefore conducted to determine the best design of specimen, gate and feeders to insure soundness. It was assumed that the design producing from a given metal the strongest and most ductile bars with the least variation as between triplicate specimens was that most conducive to soundness. About 3500 bars from some 500 heats were broken in the course of a preliminary investigation. As a result a set of specimens cast to the form and dimensions shown in Fig. 1 was decided upon and gated as the results of the preliminary test indicated as best. Variable No. 5 is thus eliminated from consideration.

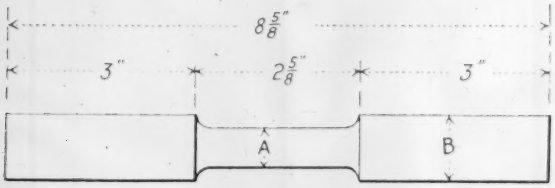
From this pattern equipment, a number of specimens of each size were cast from metal of the following composition: Carbon, 2.44 per cent; silicon, 0.76 per cent; manganese, 0.180 per cent; phosphorus, 0.166 per cent; and sulfur, 0.099 per cent. Examination of the largest specimens disclosed the absence of graphite, thus eliminating variable No. 4. The carbon content of the metal removed by machining was determined and ran from 0.09 to 0.15 per cent.

The molds were made by a highly skilled man, so that all the

[1] Standard Specifications for Malleable Castings (A 47–19), "A.S.T.M. Standards Adopted in 1919," p. 7.

specimens were unusually free from surface defects. The best one of each size was set aside for use without machining. The consequence of variable No. 6 was thus minimized as far as possible, though it of course can not be entirely overcome.

One specimen of each size was then ground for its entire gage length to a diameter $\frac{1}{8}$ in. less than its nominal diameter as



A	B
1/4"	5/8"
3/8"	3/4"
1/2"	7/8"
5/8"	1"
3/4"	1 1/8"
7/8"	1 1/4"
1"	1 3/8"
1 1/8"	1 1/2"
1 1/4"	1 5/8"
1 3/8"	1 3/4"
1 1/2"	1 7/8"

FIG. 1.—Dimensions of Test Specimens as Cast.

cast. This involved the removal of a little over $\frac{1}{16}$ in. of the surface metal in most cases.

The set of specimens originally reserved, the ground set and an additional rough set were then annealed under conditions which assured the greatest possible uniformity throughout the series. After annealing, the ground specimens had, of course, increased about one per cent in diameter. The third or rough set of annealed specimens was then turned to the same diameters as the corresponding members of the series that had been ground

to size. The two finished series were thus exactly similar to each other except as to the effect of the first variable. The series ground to size before annealing was exactly similar to the

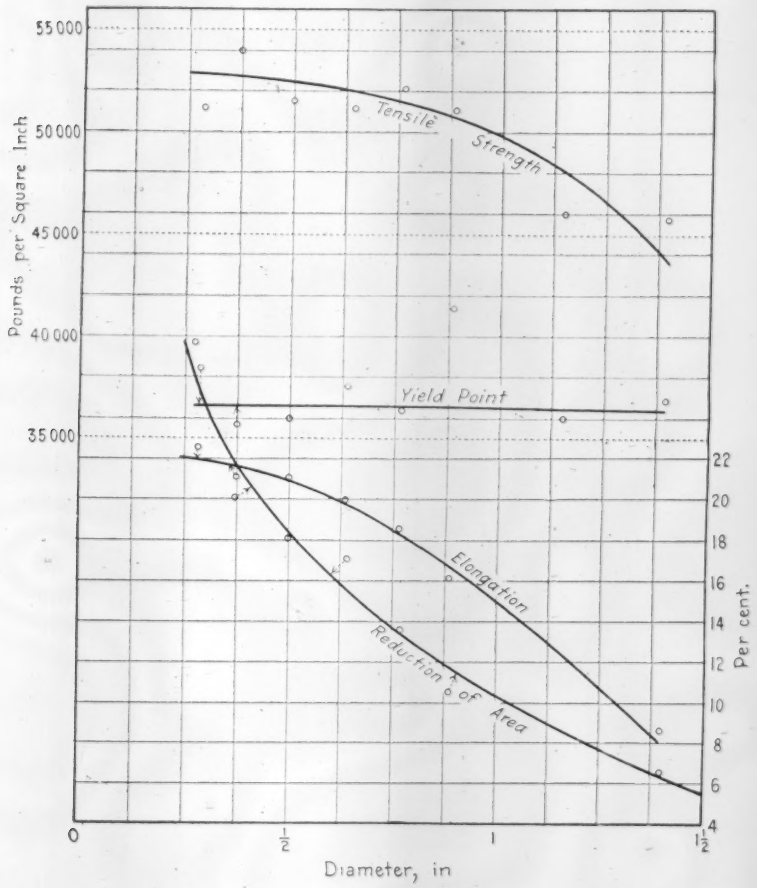


FIG. 2.—Results of Tests on Specimens Ground before Annealing.

unmachined series, except as to the effect of the second and third variables, which are related, and some residue of the effect of the sixth variable which could not be completely overcome. Each series within itself was alike, except with respect to the

third variable. An intercomparison of data from the three series should therefore permit of conclusions as to the relative effect of the first three variables.

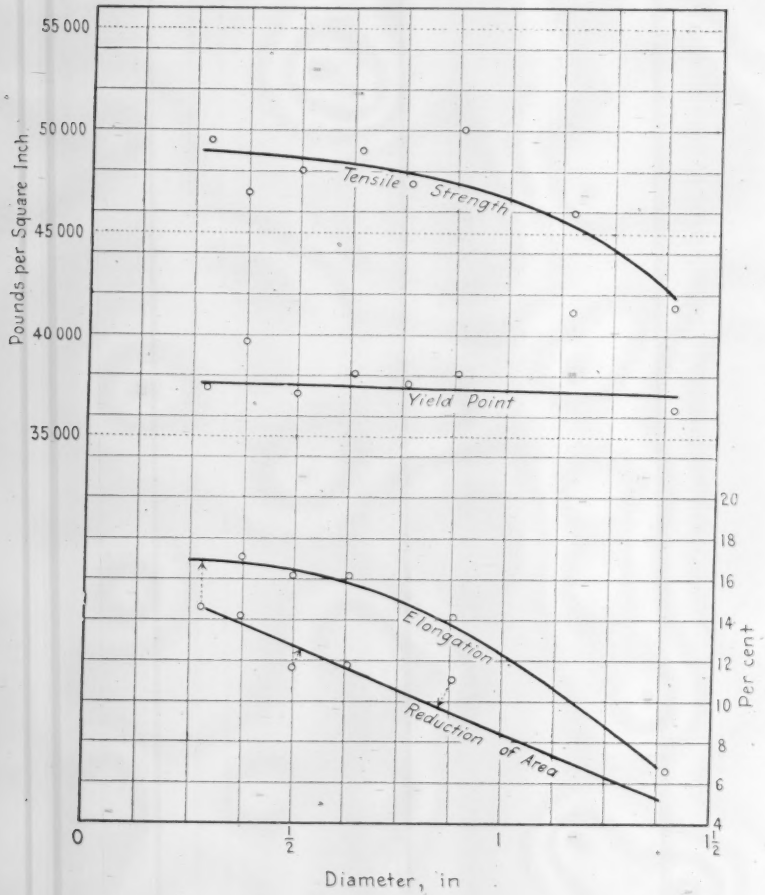


FIG. 3.—Results of Tests on Specimens Turned after Annealing.

The study of the gating problem and the production of acceptable specimens was the most difficult part of the problem, occupying about six months of experiment.

RESULTS OF TESTS.

The specimens were tested in tension. The results obtained are shown graphically in Figs. 2, 3 and 4. In the absence of a

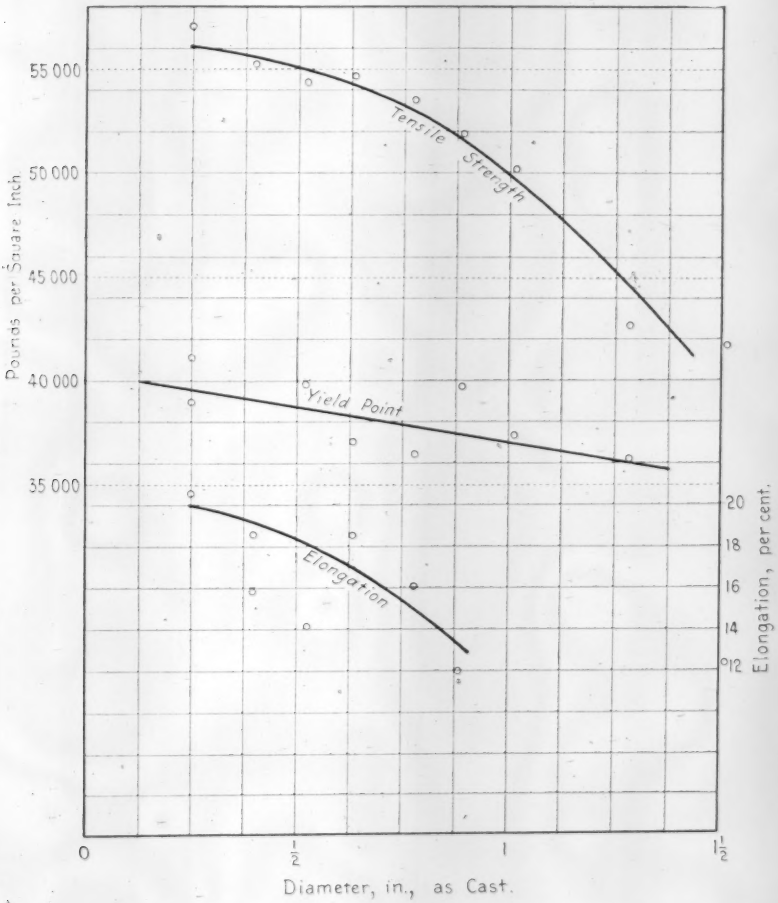


FIG. 4.—Results of Tests on Specimens not Machined.

suitable extensometer, the yield point was determined by the divider method; so the results are none too accurate. Determination of the reduction in area of unmachined specimens was omitted for it was considered unsatisfactory.

The tests show clearly the decrease in strength and ductility with increasing area of cross-section and show also that decarbonization somewhat improves the material, mainly in ductility. The fact is also brought out that the surface metal, as cast, irrespective of decarbonization, is superior to the interior metal.

It is further shown that these differences, though well defined, are not so great as to warrant the old assumption that malleable iron owes all its virtues to the decarbonized skin.

INTERPRETATION OF RESULTS.

It can be shown that the graphs given are nearly equivalent to the following equations, in which d is the diameter in inches of the specimen as tested:

	TENSILE STRENGTH, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT.
(1) Unmachined	$56\,000 - 5\,384\ d^3$	$20 - 8.01\ d^{2\frac{1}{2}}$
(2) Machined before annealing	$53\,000 - 3\,231\ d^3$	$22 - 6.58\ d^{2\frac{1}{2}}$
(3) Machined after annealing	$49\,000 - 2\,462\ d^3$	$17 - 6.29\ d^{2\frac{1}{2}}$

Within the limitations of accuracy of the method used for its measurement, the yield point may be said to be nearly constant. Comparison of the reduction of area is omitted, first because the determination can not be made on cast specimens, second because the two graphs do not follow curves of similar equation, and third because the determination is not commerically applied to this product. The tensile strength of rough specimens and the elongation of specimens machined after annealing depart somewhat more from the calculated values than the other data.

The effect of decarbonization alone on tensile properties may be obtained by subtracting Eq. 3 from Eq. 2 and is a decrease of $4000 - 769\ d^3$ lb. per sq.in. in tensile strength and $5 - 0.29\ d^{2\frac{1}{2}}$ per cent in elongation.

An attempt to compare Eq. 1 with Eq. 2 must include considerations of the fact that specimens of diameter d in Eq. 2 had a diameter $d + 0.125$ in Eq. 1. The graph for tensile strength plotted from Eq. 1 intersects that plotted from Eq. 2 at a value of d (as cast) of about 0.9. Thus, a bar annealed with its original surface is stronger than one annealed after grinding

if the original diameter is less than 0.9 in., and weaker if the diameter is greater. The variation is from 2700 lb. stronger to 3200 lb. weaker in the range investigated. The elongation is always less for a cast specimen, the range being from 2 per cent less at a diameter of $\frac{1}{4}$ in., to 5 per cent less at a diameter of 1 in.

The crossing of the two graphs for tensile strength is of course due to the superimposing of two effects, that of the chilled surface which is beneficial and that of the rough surface which is harmful. The former predominates in small, the latter in large specimens.

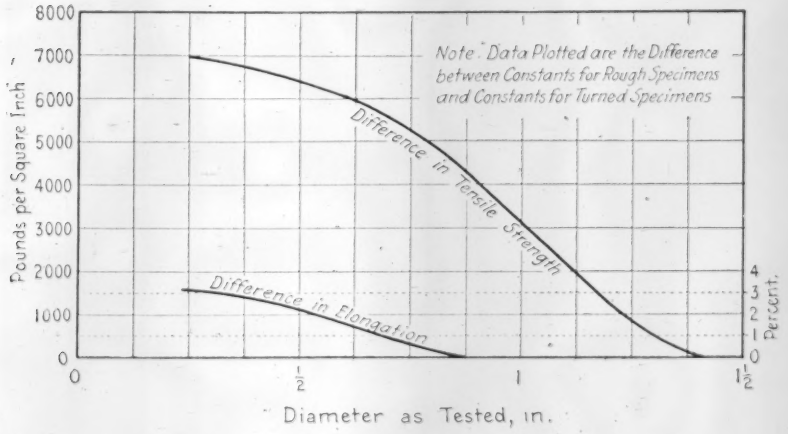


FIG. 5.—Comparison of Tensile Properties of Machined and Cast Speicmens of Equal Diameters.

For the use of the designer, the difference in strength and elongation of specimens cast to size and of specimens machined to the same size is summarized in Fig. 5.

To test the effect of varying degrees of decarbonization on metal of a given composition, there were selected from operating records a series of tests on A.S.T.M. specimens originally containing between 2.40 and 2.60 per cent total carbon, and between 0.70 and 0.80 per cent silicon. After annealing, these contained from 0.78 to 1.79 per cent carbon on a true average cross-section.

The physical properties of the individual specimens vary on account of variations in both original and final total carbon.

The results when averaged for groups having a range of 0.10 per cent each in final total carbon, and an average close to 2.50 per cent carbon as cast, are quite concordant as shown graphically in Fig. 6.

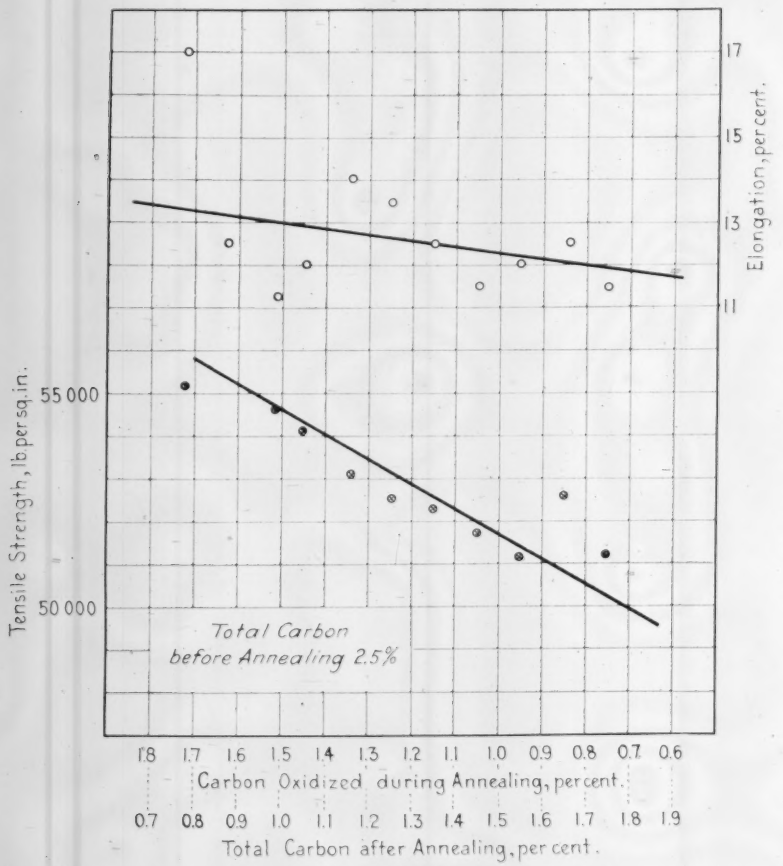

Tensile Strength, lb per sq. in.
55 000
50 000
17
15
13
11
Elongation, per cent.
Total Carbon
before Annealing 2.5%
1.8 1.7 1.6 1.5 1.4 1.3 1.2 1.1 1.0 0.9 0.8 0.7 0.6
Carbon Oxidized during Annealing, per cent.
0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
Total Carbon after Annealing, per cent.

FIG. 6.—Effect on Tensile Properties of Varying Degrees of Decarbonization.

CONCLUSIONS.

The exact numerical data in the present experiment hold true, of course, only for the particular metal and heat treatment

involved. Some generalizations are, however, probably justified and may lead to the following conclusions of general application:

1. Decarbonization has a favorable influence upon the strength and ductility of the product.

2. The effect of quick cooling in freezing on the surface metal of a casting is such as to improve the strength and ductility of the product.

3. Roughness of surface of a cast specimen apparently decreases the strength and especially the ductility.

4. The ultimate strength decreases with increasing diameter of section by an amount proportional to the cube of the diameter.

5. The elongation decreases by an amount proportional to the $2\frac{1}{2}$ power of the diameter.

6. The combined effect of all three of the preceding variables on strength amounts to about 7000 lb. per sq. in. for sections $\frac{1}{4}$ in. in diameter or less, and becomes negligible at diameters of $1\frac{1}{4}$ in. or over.

7. The combined effect on elongation is about 3 per cent for small specimens and negligible for diameters above $\frac{3}{4}$ in.

8. The yield point is apparently not affected by any of the variables investigated.

CHAIN CABLE AND SOME OF ITS PHYSICAL PROPERTIES.[1]

By C. G. Lutts.

Introduction.

In 1808, chain cable was first used in place of hemp or other rope. It immediately proved its superiority, and by the middle of the century it had come into general use. Not long after, laws were enacted, making it compulsory for certain classes of vessels to carry chain that had been proved. The law requiring a test of every chain cable was perhaps the greatest advance that has been made in the chain industry. It has stimulated the development of new processes of manufacture, and has consequently made the different phases of inspection rigid.

Progress has been made in the manufacture of chain cable—not the sensational developments that have occurred in some industries, but, nevertheless, progress commensurate with the difficulties to be surmounted. The first chains were made by hand, and even to-day certain sizes are still fashioned by hand. It is in the larger sizes that necessity has demanded new processes. The hand method of chain making was suitable for the smaller sizes, but with the increase in size of the chain and its consequent heavier demands on human energy for its manufacture, together with the limited production, the introduction of power became necessary.

The power-welding process was adopted at the Boston Navy Yard in 1914. Although troublesome at first as are other new departures, it soon proved itself to be the needed advance, not only in the rate of production, but also in the quality and uniformity of product. Uniformity of product is a requisite in chain. For this reason alone the adoption of the power process has been justified. With its introduction at the Boston Navy Yard, certain manufacturing steps and properties of chain cable began to be considered and studied. This paper will contain certain results from these records, the author hoping that, at

[1] This paper is published by permission of the Secretary of the Navy.

least in some of its phases, it may be useful both to the manufacturer and to the user of the chain.

MANUFACTURE OF POWER-FORGED CHAIN AT THE BOSTON NAVY YARD.

As it is the intention to confine this paper rather to records and discussions of certain physical properties of chain cable than to a description of its manufacture, it should be borne in mind that the present description of the material used and the manufacturing operations are given only in outline. They will, however, serve as a means of comparison and interpretation of the results.

Material.—The material chosen for chain cable has always been wrought iron. Much has been written about the unsuitability of steels for welding. Without attempting to discuss the reasons for and against the use of steel in chain making, it may be interesting to know that at the Boston Navy Yard, experimental chain cables have been made of soft steel, that these cables are of the same strength and ductility as wrought-iron chain cables, and that they are giving equally as satisfactory results in service. Like many other vital changes, it appears to be necessary to accept the idea, to develop experience and machinery to fulfil it, and to apply it in production over a considerable period of time, before the final decision relative to its suitability can be made. The outcome of such a period of production is not now known, and the best available grades of wrought iron are still in use for producing Navy chain.

The Government specifications for wrought iron are, in part, as follows:

> "Wrought iron for the manufacture of chain.
>
> "The material shall be of the best quality of American refined iron, free from any admixture of steel or scrap."
>
> "Grade 'A' iron will be double refined and is to be used principally for the manufacture of chain for ships' cables."
>
> "The physical requirements for Grade "A" iron are:

Minimum tensile strength, lb. per sq. in.....	48 000
Minimum yield point, " "	0.5 tens. str.
Minimum elongation in 8 in., per cent.....	26
Minimum reduction of area, per cent.....	40

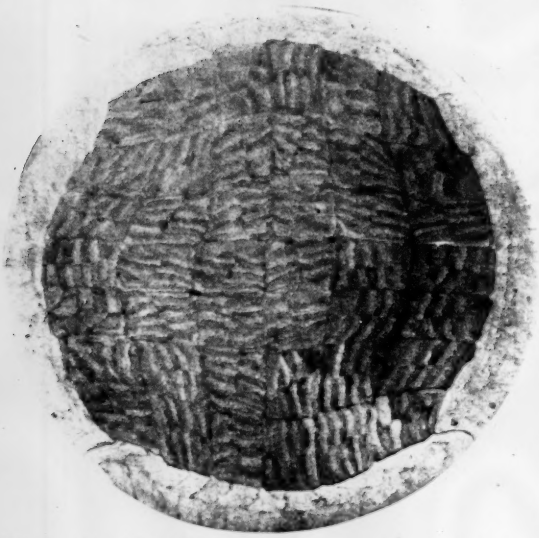


FIG. 1.—Grade "A" Wrought Iron. Showing Method of Piling. Developed by Etching a Polished Full Cross-Section of Bar. Etched with five-per-cent Nitric Acid in Alcohol.

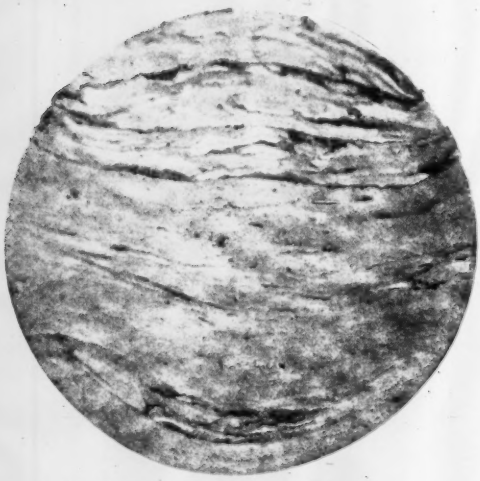


FIG. 2.—Grade "B" Wrought Iron. Showing Method of Piling. Developed by Etching a Polished Full Cross-Section of Bar. Etched with five-per-cent Nitric Acid in Alcohol.

"The chemical requirements for Grade "A" iron are:

Maximum amount of phosphorus, per cent	0.10
Maximum amount of sulfur, per cent	0.015

"Material will be tested in sizes rolled where practicable, and for each ton or less of each size the following tests will be made: one tensile, one cold bend, one quench bend, one nick bend, and one drift test."

It may be noted that Grade "A" or double-refined iron is required for use in the manufacture of chain. Figs. 1 and 2 illustrate the differences in piling of Grade "A" and Grade "B" irons. Grade "A," made from a number of Grade "B" iron bars rolled together at a welding temperature, is more uniform and contains less slag than Grade "B" iron. The slag content by volume in Grade "A" iron as used at the Boston Navy Yard is found to be between 2.5 and 3 per cent. Figs. 1 and 2 also make clear the reason for the superiority of Grade "A" iron in the various tests, and especially in the drift test.

After considering the records of many tests, it is believed that the requirements are reasonable, and that good grades of wrought iron should meet the specifications. The average strength of the wrought irons in use, in the air-cooled condition, is close to 49,000 lb. per sq. in. The same stock irons average 35 per cent elongation in 8 in. and 50 per cent reduction of area.

Chemical analyses of the stock irons show the carbon content to be between 0.05 per cent and 0.08 per cent. The phosphorus and sulphur contents are within the limits set; the manganese is very low.

Manufacturing Steps.—The first operation of the process consists in shearing the round wrought-iron bar into "bolts." These "bolts" are placed in steel baskets and are transported to the upsetting machine. Near the upsetting machine there is located a heating furnace. Eight or more bolts are placed for about a foot of their length into the heating chamber of this furnace. At the proper forging heat each successive bolt is removed and its heated end inserted into an upsetting machine, the shank of the bolt is gripped and the header comes forward and upsets the hot end. Without reheating, the bolt is placed under a drop-hammer and scarfed. It is then heated again in the furnace and the other end scarfed. The bolt scarfed on

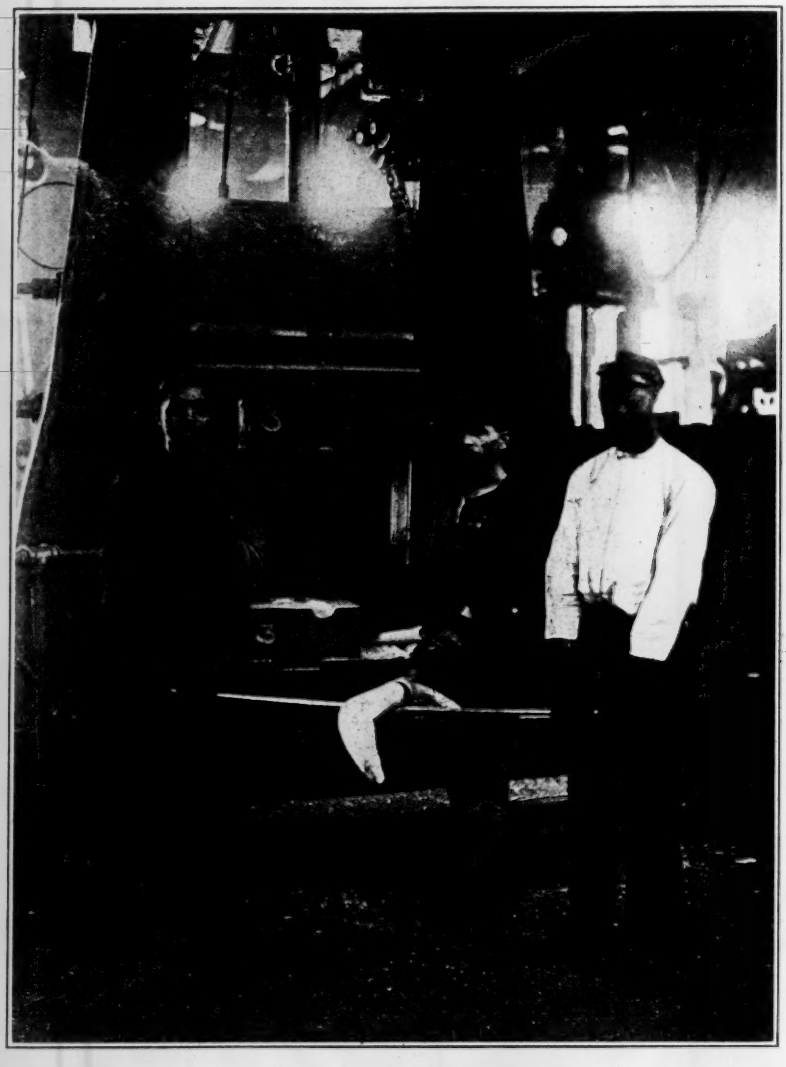


FIG. 3.—Bolt Scarfed on Both Ends.

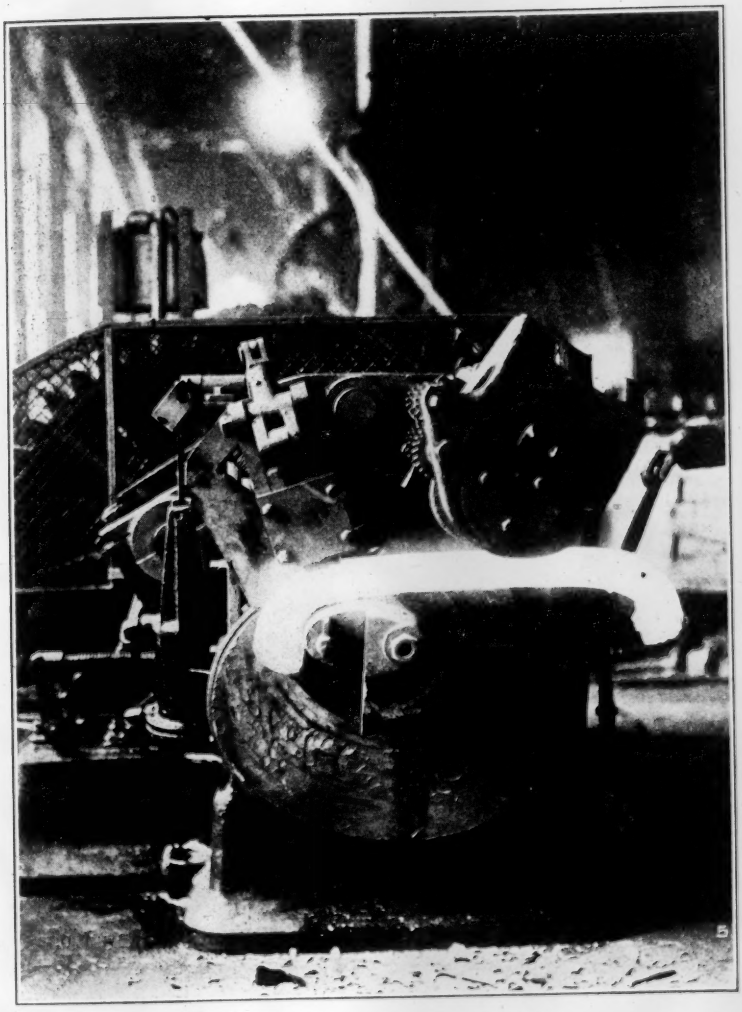


FIG. 4.—Bolt Ready to be Bent.

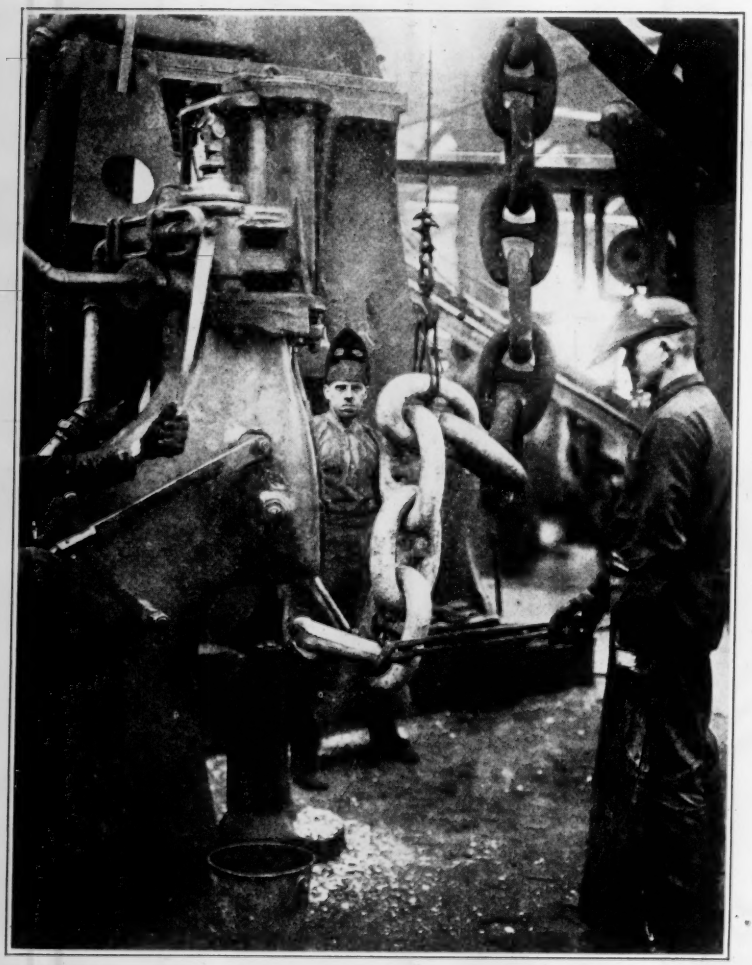


FIG. 5.—Welding on "Dolly" Dies.

both ends is shown in Fig. 3. The accomplishment of this step is made easy by having the furnace, the upsetting machine, and the scarfing hammer in an arc of a circle convenient to one another. The scarfed bolt is then bent into the form of a link with the ends open. The machine for performing this operation is shown in Fig. 4. The bolt is heated in a furnace situated near by and is set on top of the mandril. A pneumatic clamp descends and holds the bolt securely in place; a roller then wipes the bolt around the mandril and automatically returns to its original position. The link now has its ends or scarfs apart; this is accomplished by means of the spiral shape of the mandril. The links are then transported to the welding plant for the succeeding steps in the process.

Each welding plant consists of two chain fires, two cranes, two small single-frame steam-forging hammers, and one large steam-forging hammer. Two gangs of men work at each plant, using the large steam-forging hammer between them, this hammer having double impression dies, permitting use on opposite sides. A preheating furnace is conveniently located.

The step of welding begins at the completion of the last welded link in the chain. A preheated link is threaded into this last link. The chain with its threaded link is swung over and the threaded-link scarfs closed under the heavy steam-forging hammer. Again swinging the crane so as to bring the chain over the fire, the link is lowered into the oil-fired forge for its welding heat. At the proper moment, the link, white hot and dripping with slag, is swung onto the small hammer called the "dolly" hammer (Fig. 5). The welding proper is accomplished by this fast-working hammer. As the dolly hammer does not give the perfect shaping desired, the link, without being reheated, is immediately swung over onto the finishing dies of the heavy steam-forging hammer, and there is struck several times on both sides. The link is now perfect in form and carries a small flash at the welded end, which is cut off with a chisel. The link is then smoothed free of any surface imperfections.

The setting of the stud is accomplished by standing the link on its side in a special recess in the finishing dies of the heavy steam-forging hammer and holding the stud in place by the use of a pair of tongs. The hammer closes the link, thus

gripping the stud firmly. The link is now finished and ready for the threading of the next new link.

Breaking Tests.—It is a requirement that at least one breaking test be performed on each shot of chain manufactured. Under certain conditions, as when the routine is disturbed by new sizes or by the introduction of a new man to the force, or when the foreman deems it advisable, a number of tests may be made on a shot. The samples taken for these tests are usually two links secured by cutting off, by means of an acetylene torch, the last two links of the chain while it is under process of manufacture. To make the test independent of any attempt on the part of the chain maker to improve it, the sample is removed at any time during the manufacture. These test samples, after annealing with the regular charge, are broken in a 2,000,000-lb. hydraulic testing machine and the results recorded.

Heat Treatment.—Prior to the introduction of power welding at the Boston Navy Yard, extensive experiments were carried on toward the development of this process, but something appeared to be lacking. Links, apparently perfect and having been welded much better than was ever done by hand, would, under test, break short, deficient in that toughness and ductility associated with wrought iron. Believing that a heat treatment or an anneal was the necessary remedy, and having previously found that test triplets when subjected to an approximate annealing temperature would give excellent results, steps were taken to equip a laboratory and to have a study made of the heat treatment of wrought-iron chain cable. The results of this study have been published.[1] It was found, as one of the main conclusions, that chain made by the power-forging process possessed an overheated, distorted structure at the welded ends of the links. This type of structure is shown by Fig. 6. The salient features are the large grains and the elongated bands of pearlite, a structure indicative of weakness and found to be a definite cause of unreliability in chain. The corrective treatment was found to consist of a proper anneal: heating for a short period of time above the Ac_3 point and cooling at a certain rate to obtain the desired physical

[1] Webster and Patch, "Heat Treatment of Wrought-Iron Chain Cable," *Journal*, Am. Soc. Mech. Eng., December, 1916.

properties. Fig. 7 represents the sample illustrated by Fig. 6, but after having been heated to 950° C. and cooled in air. The sections shown by these photomicrographs contain more than the average amount of carbon found in the link. This selection was made because it illustrates the overheated structure better than sections with no carbon. Thus the desired improvement is made, the grains are equiaxed; the criterion for the treatment is the fact that annealed chain gives excellent results under test and in service. In the power-forging process for chain, it is natural for scarfs to be lengthened so as to have a longer weld

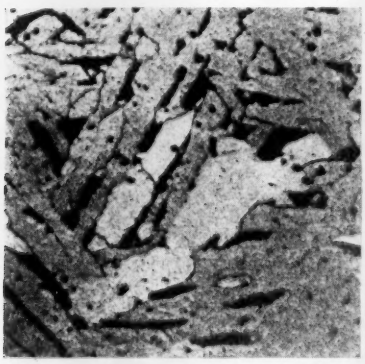


FIG. 6.—Welded End before Annealing. Overheated, Distorted Structure. Constituents as Elongated Bands (×100). Etched with Nitric Acid in Alcohol.

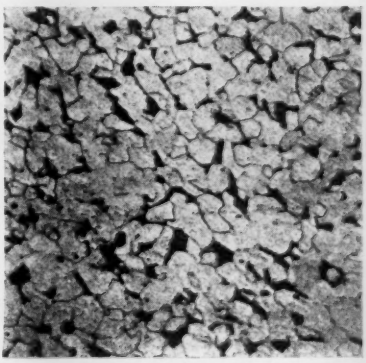


FIG. 7.—Welded End after Heating to 950° C. and Air-cooling. Normal Structure (×100). Etched with Nitric Acid in Alcohol.

and thus derive the advantage of having a more reliable, welded link. As this necessitates the heating of a larger section of the link, there is no doubt that power-welded chain is subjected to a uniformly higher temperature than hand-made chain, and, in addition, due to the comparative rapidity of the process, is finished higher above the critical range and cools down through a longer range of temperature, during which time conditions are favorable for grain growth. Webster and Patch[1] have shown that the grain size is largest at the welded quarters, the explanation being that these sections receive less work than

[1] *Loc. cit.*

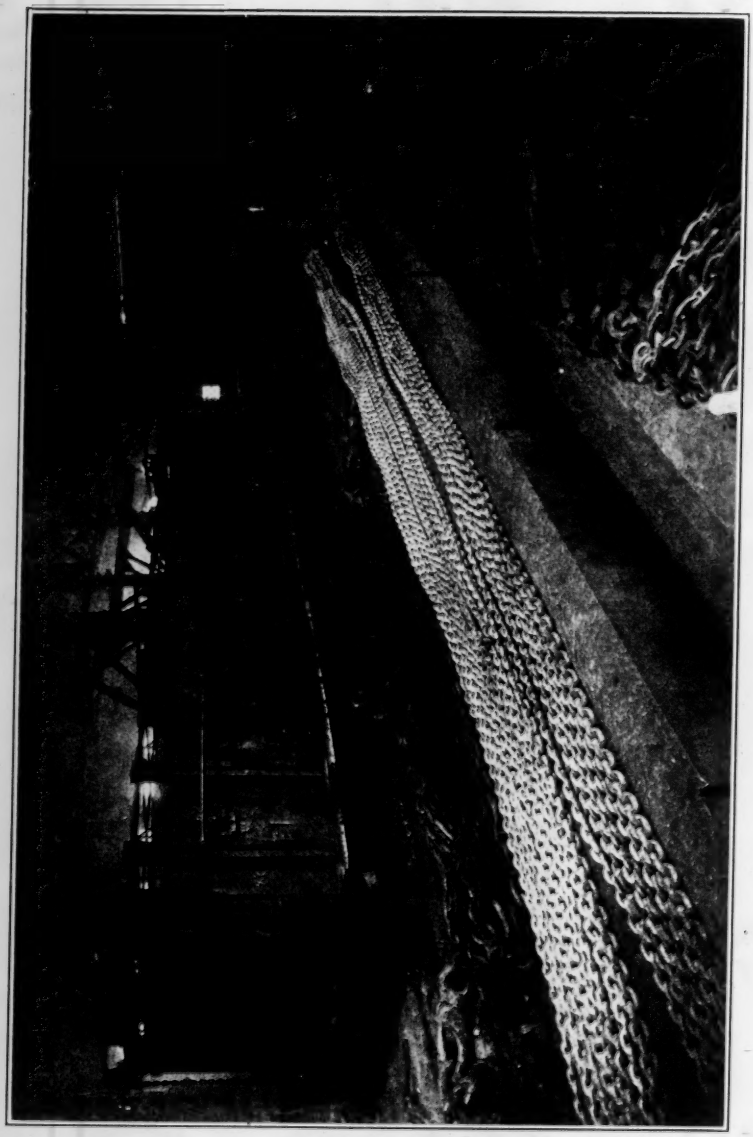


FIG. 8.—Chain Annealing Furnace and Proving Pit.

does the welded crown of the link, while the temperature is about the same. Grain growth has been found to occur in hand-welded chain also, so it would seem that proper annealing should result beneficially for this smaller chain. It has been found that the rate of cooling from the annealing temperature is an important factor toward determining the strength and impact resistance of wrought iron and wrought-iron chain. Cooling in the furnace is not desirable, since it results in low values for the strength and the hardness of the metal. In spite of the probable superiority of an oil quench, air cooling has, because of extensive equipment necessary for quenching in oil, been accepted as the standard treatment.

Fig. 8 shows the furnace now in use for annealing power-forged chain. This furnace is of the over-fired car bottom type. The chain is loaded onto the car, which has inserted at its front end an 8-ft. thermocouple, so placed that the charge rests upon it. Through the furnace walls eight other thermocouples project into the furnace near the top of the charge. The leads from these couples extend to a booth located on the opposite side of the furnace, where the temperatures are read by the furnace heater. The potentiometer system is in use. In addition to the potentiometer readings obtained at the booth, there is a central recording instrument on which are obtained the temperature records of the thermocouple beneath the charge and two furnace thermocouples. The furnace is brought to the required temperature of 950° C. for the thermocouple beneath the charge, and a maximum temperature of 980° C. for the thermocouples above the charge. The time required for heating is approximately three hours. The correct temperature having been obtained, the charge is held at this point for ten minutes, at the end of which time the car is drawn out and the chain allowed to cool in the air.

Proving.—The shot of chain, after cooling, is ready for the proof test. The runway used is shown in Fig. 8, the testing machine being located in the room shown at the right hand side of the photograph. The chain is fastened at the near end (not shown) to an anchor crosshead, and at the farther end to the straining crosshead, forming a moving part of the 2,000,000-lb. hydraulic testing machine. The required proof load, as given

by the Navy Department tables, is applied and the elongation of the shot is recorded. It may be mentioned that the original length of the shot is such that after proving the required length of 90 ft. is met within a few inches either way. Various link measurements are taken to determine their conformity to the specifications. Each link is then carefully inspected for the presence of flaws or defects. Finally, if the shot is found satisfactory, it is numbered, given a coating by pulling through a bath of hot asphaltum and turpentine, and shipped to the chain stores.

THE STRENGTH OF NAVY CHAIN CABLE.

As was mentioned before, it has been the practice to obtain from each shot of chain, as manufactured, one or more tests. The results of these tests are valuable, not only in maintaining the efficiency of the work, but, also in giving, when averaged by months and years, practical information relative to the average strength of chain.

Testing Machines.—Until November, 1918, tests were made by means of an 800,000-lb. lever-type testing machine. This machine had been in service at the Boston Navy Yard for a number of years, but, because of the increasing size of chain, it became necessary to install a larger capacity machine. A new machine, a 2,000,000-lb. Olsen chain tester, was placed in service in November, 1918; with it all tests have since been made. The results obtained from both machines are considered accurate. The 800,000-lb. machine was calibrated by the Bureau of Standards in May, 1917. The 2,000,000-lb. machine was calibrated at the time of installation by means of calibrating levers, furnished with the machine. The 2,000,000-lb. machine is a modification of the Emery type of machine.

Classification of Breaks.—The method of reporting the nature and location of breaks has been the subject of some thought. In general, it is believed that the more simple the method, the more accurate would be the test-card designations, and the more readily the results could be interpreted. Normally, there are three divisions of results: first, a low breaking load, second, the average breaking load, and third, an excellent breaking load, one that is well over the requirements. Now, it happens

that, as a rule, each of these groups corresponds to a certain type of break. A low breaking load occurs if the welding temperature is too low, failure taking place by the slipping of the welded surfaces. This is termed a weld break. A link overheated and burned will also give a low breaking-load figure. Fortunately, the burned link condition is not common in power-forged chain. Although the burned-link break is by no means considered a weld break, the cases are so few—under one per cent—that, in order to simplify the record, their type of break is included among the weld breaks, it being understood that the two types of failure are common in that they result from imperfect welding. The average break may be classified as a welded-quarter break. It includes any break occurring at the welded half of the link which clearly shows that it is not a slipping of the welded surfaces or a burned metal break. As indicated, it usually takes place at the welded quarters and as a rule follows a portion of the weld and then breaks across the metal. The third type of break is the bent-end break. It includes any break occurring at the end of the link opposite the weld, and naturally is the best break that can be obtained from a link of uniform cross-section. The matter of designation of breaks, therefore, seems to confine itself to three locations, each typical and truly representative of the work performed and the strength of the link. These designations are weld breaks, welded-quarter breaks and bent-end breaks. The results are so classified in the tables.

Tables and Discussions.—Table I gives the Government requirements for the dimensions of the common links, the proof loads and the breaking loads for stud-chain cable, sizes $2\frac{1}{4}$ in. to $3\frac{1}{4}$ in., inclusive.

The term "size of cable" gives the nominal diameter of the stock used in the chain. The $2\frac{1}{4}$-in. stock is allowed a plus tolerance of $\frac{1}{32}$ in. All larger sizes are allowed a plus tolerance of $\frac{1}{16}$ in. One other dimension, that of the welded-end diameter, is valuable in order to describe completely the exact dimensions of the links, the tests of which are given in the tables. In order to correct a deficiency in strength of the link at the welded end, it has been the custom at the Boston Navy Yard to have the impression in the finishing dies slightly larger than the diameter of the stock. The increase in diameter for the welded end of links over the diameter of the stock averages $\frac{3}{32}$ in.

Table II gives the breaking loads and the location of the breaks for $2\frac{3}{4}$-in. stud chain over a period of four years—September, 1915, to September, 1919. The table also denotes the number of tests made and the number failing to pass the required proof load and required breaking load. The table is similar to the form used for monthly averages.

An examination of Table II shows that the average breaking load for $2\frac{3}{4}$-in. stud chain is, for every month, well above the requirements. The lowest monthly average is 478,000 lb. The highest monthly average is 527,000 lb. Although these values vary considerably, it may be seen that, as a whole, the variation

TABLE I.—STUD CHAIN CABLE: NAVY DEPARTMENT SPECIFICATION 6c6a (TABLE IN PART).

Size of Cable, in.	Extreme Length of Link, in.	Extreme Width of Link, in.	Inside Radius of End, in.	Required Proof Load, lb.	Required Breaking Load, lb.
$2\frac{1}{4}$	$12\frac{7}{8}$	$8\frac{1}{8}$	$1\frac{5}{16}$	182 000	303 300
$2\frac{3}{8}$	$13\frac{1}{2}$	$8\frac{1}{2}$	$1\frac{3}{8}$	201 700	336 200
$2\frac{1}{2}$	$14\frac{1}{4}$	9	$1\frac{7}{16}$	225 500	370 800
$2\frac{5}{8}$	15	$9\frac{1}{2}$	$1\frac{1}{2}$	244 200	407 000
$2\frac{3}{4}$	$15\frac{5}{8}$	$9\frac{7}{8}$	$1\frac{9}{16}$	266 800	444 700
$2\frac{7}{8}$	$16\frac{3}{8}$	$10\frac{3}{8}$	$1\frac{5}{8}$	290 500	484 100
3	$17\frac{1}{8}$	$10\frac{3}{4}$	$1\frac{3}{4}$	315 000	525 000
$3\frac{1}{8}$	$17\frac{7}{8}$	$11\frac{1}{4}$	$1\frac{13}{16}$	340 500	567 500
$3\frac{1}{4}$	$18\frac{1}{2}$	$11\frac{3}{4}$	$1\frac{7}{8}$	367 000	612 000

from month to month is low. It has been calculated that the average variation from month to month is 1.8 per cent. Again the highest variation amounts to 5.2 per cent; this particular instance occurring in the months of September, 1918, and December, 1918. The number of tests in September was small. Of these 75 per cent were bent-end breaks. These facts together with a change of testing machines, made conditions most favorable for a high variation. A method for determining the uniformity of the product from month to month is available. For instance, should the monthly average show a breaking load differing from that of the previous month by over 5 per cent, it would immediately become apparent that some radical change,

TABLE II.—$2\frac{3}{4}$-IN. STUD CHAIN MONTHLY AVERAGES.

(Required Breaking Load, 444,700 lb. Values expressed in thousands of pounds.)

Year and Month.	Weld Breaks.		Welded-Quarter Breaks.		Bent-End Breaks.		Total Breaks.		Number Failing to Pass Proof Load.	Number Failing to Pass Breaking Load.	Annealing Temperature, deg. Cent.
	Number.	Average Breaking Load.	Number.	Average Breaking Load.	Number.	Average Breaking Load.	Number.	Average Breaking Load.			
1	2		3		4		5		6	7	8
1915.											
September	2	492	0	...	4	497	6	495	0	0	900
October	7	482	9	476	5	496	21	483	0	2	900
November	10	469	12	477	3	510	25	478	0	1	900
December	3	471	23	480	16	518	42	494	0	3	900
1916.											
January	2	516	29	471	8	514	39	482	0	6	900
February	5	481	37	492	16	535	58	503	0	6	900
March	6	475	23	508	16	535	45	513	0	0	950
April	5	473	17	514	12	540	34	517	0	1	950
May	4	490	24	504	10	529	38	509	0	1	950
June	4	460	31	496	5	522	40	496	0	5	950
July	5	491	32	496	8	517	45	499	0	3	950
August	3	441	30	492	3	527	36	491	2	2	950
September	0	...	6	510	3	525	9	515	0	4	950
October	2	486	15	508	12	523	29	513	0	0	950
November	4	493	10	495	16	525	30	511	0	0	950
December	2	484	23	501	16	521	41	508	0	0	950
1917.											
January	8	468	17	504	19	517	44	503	0	2	950
February	1	511	24	490	17	520	42	503	0	0	950
March	2	487	4	517	20	514	26	512	0	0	950
April	14	479	10	489	32	506	56	496	0	1	950
May	8	474	20	490	42	508	70	499	0	1	950
June	3	477	11	482	30	502	44	495	0	0	950
July	4	496	23	481	25	507	52	495	0	3	950
August	3	494	31	500	15	527	49	508	0	1	950
September	2	515	19	517	18	540	39	527	0	1	950
October	0	...	9	508	24	532	33	525	0	0	950
November	3	478	8	509	42	530	53	524	0	0	950
December	4	456	14	498	37	521	55	510	0	2	950
1918.											
January	2	491	8	515	7	524	17	516	0	0	950
February	0	...	0	...	0	...	0	...	0	0	...
March	1	523	14	512	28	526	43	521	0	0	950
April	0	...	0	...	0	...	0	...	0	0	...
May	0	...	0	...	0	...	0	...	0	0	...
June	0	...	0	...	0	...	0	...	0	0	...
July	1	473	3	507	8	522	12	514	0	0	950
August	1	481	5	480	8	523	14	505	0	0	950
September	0	...	2	509	6	525	8	521	0	0	950
October	0	...	0	...	0	...	0	...	0	0	...
November	0	...	0	...	0	...	0	...	0	0	...
December	17	481	19	484	14	523	50	494	0	3	950
1919.											
January	27	496	15	516	29	529	71	514	0	0	950
February	1	473	13	513	16	528	30	520	0	0	950
March	6	491	11	517	26	531	43	522	0	0	950
April	6	501	4	521	25	522	35	518	0	0	950
May	2	490	6	509	8	526	16	515	0	0	950
June	0	...	0	...	0	...	0	...	0	0	950
July	1	496	4	474	3	519	8	494	0	1	950
August	0	...	0	...	0	...	0	...	0	0	...
September	0	...	0	...	0	...	0	...	0	0	...

either in material or workmanship, had taken place. Considered in its entirety, column No. 5 of Table II shows a uniformity that is satisfactory.

It is interesting to know that tests performed on doublets from an experimental steel cable resulted in an average breaking load which approximates closely the average breaking load of wrought-iron cable as given in column No. 5. This is natural, since the steel used for this particular steel cable was so chosen as to have physical properties closely resembling those of wrought iron.

In columns Nos. 2, 3, and 4, it is seen, provided that the total number of tests is sufficient, that the bent-end breaks are the strongest, the welded-quarter breaks are the next strongest, and the weld-breaks are the weakest. This condition is, of course, natural. The figures, however, emphasize the desirability of a maximum of bent-end breaks.

In column No. 6, two failures are recorded under the proof load out of a total number of 1448 tests.

Column No. 7 shows a total of 49 failures under the breaking load, out of 1448 tests. Expressed as a percentage, it shows that 3.4 per cent failed to pass the requirements. Through the period of four years there have been a number of changes in the chainmakers' personnel, involving the teaching of new men. Many of the failures shown in the column may be attributed to this cause, as all tests made have been entered. It is considered that failures amounting to only 3.4 per cent are very low for the chain industry.

Table III gives the grand averages of stud-link chain, as manufactured at the Boston Navy Yard. For five of the sizes, the average is calculated for a period of four years. Other data, such as number of tests, locations of breaks, and breaking loads are included.

Table IV has been calculated in the form of percentages, based on the figures of Table III. In this form the results of breaking loads and the locations of breaks may be more easily studied.

Column No. 8 of Table IV shows that the breaking load of Navy Chain Cable averages approximately 12 per cent over the requirements. By comparing columns Nos. 3, 5, and 7, it may

be observed that the bent-end excess over requirements is greater in every case than that exhibited by welded-quarter excess over requirements. Likewise, column No. 5 bears the same relation to column No. 3 with the single exception of the $2\frac{5}{8}$-in. size. Here it is seen that the weld breaks for this size were low in number. It is probable that the exception in this case was caused by the small number of tests. The percentage of breaks

TABLE III.—SUMMARY OF STUD CHAIN TESTS.

(Grand Averages, taken from Monthly Averages.)

(Load values expressed in thousands of pounds.)

Size of Chain, in.	Time Range of Tests.		Weld Breaks.		Welded-Quarter Breaks.		Bent-End Breaks.		Total Breaks.		Number Failing to Pass Proof Load.	Number Failing to Pass Breaking Load.	Annealing Temperature, deg. Cent.	Required Breaking Load.
	Month, Year.	Month, Year.	Number.	Average Breaking Load.	Number.	Average Breaking Load.	Number.	Average Breaking Load.	Number.	Average Breaking Load.				
1	*2*		*3*		*4*		*5*		*6*		*7*	*8*	*9*	*10*
$2\frac{1}{4}$	Sept., '15	Sept., '19	59	314	247	333	157	350	463	336	0	48	950	303
$2\frac{3}{8}$	Jan., '18	Sept., '19	3	369	5	379	10	391	18	384	0	0	950	336
$2\frac{1}{2}$	Sept. '15	Sept., '19	89	396	428	410	150	429	667	411	0	66	950	371
$2\frac{5}{8}$	Sept., '15	Sept., '19	17	451	134	447	259	463	410	457	0	7	950	407
$2\frac{3}{4}$	Sept., '15	Sept., '19	181	485	615	499	652	521	1448	506	2	49	950	445
$2\frac{7}{8}$	Jan., '18	Sept., '19	1	521	5	551	14	561	20	556	0	0	950	484
3	Jan., '18	Sept., '19	4	570	19	583	27	604	50	593	0	1	950	525
$3\frac{1}{8}$	Jan., '18	Sept., '19	3	639	...	...	...	...	3	639	0	0	950	568
$3\frac{1}{4}$[a]	Sept., '15	Sept., '19	...	...	...	...	...	...	1117	Above 612	0	63	950	612

[a] No breaking tests of $3\frac{1}{4}$-in. chain were made because high strength of this chain made it inadvisable to test it in the 800,000-lb. testing machine originally used. Proof tests, however, were made on all test doublets, and a breaking load of 612,000 lb. applied.

occurring at the bent end, column No. 6, is indicative of the value of the power-forging process, since it has been the experience that commercial, hand-welded chain seldom breaks at the bent end.

The results recorded in column No. 9—"Percentage failing to pass Proof Load"—indicate the chain as being nearly perfect with regard to its "Proof Strength." In column No. 10 the $2\frac{1}{4}$ and $2\frac{1}{2}$-in. sizes are attributed with failures to pass the required breaking load amounting to 10 per cent. These,

however, are maximum figures and do not exactly represent chain which goes into service. That is, many of these failures are of chain made by new men. The $2\frac{1}{4}$ and $2\frac{1}{2}$-in. sizes were especially affected by the instruction of new men, made necessary by the war demands for increased production in these sizes. Another factor also enters to make this percentage high. After proving, or at any period during the process of manufacture, the chain is closely watched for the appearance of poor links.

TABLE IV.—PERCENTAGES DERIVED FROM FIGURES OF TABLE III.

Size of Chain, in.	Weld Breaks.		Welded Quarter Breaks.		Bent-End Breaks.		Total Breaking Load Excess Over Requirements, per cent.	Percentage Failing to Pass Proof Load.	Percentage Failing to Pass Breaking Load.
	Percentage.	Weld-Breaking Load Excess Over Requirements, per cent.	Percentage.	Welded-Quarter Breaking Load Excess Over Requirements, per cent.	Percentage.	Bent-End Breaking Load Excess Over Requirements, per cent.			
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
$2\frac{1}{4}$	13	4	53	10	34	16	11	0	10
$2\frac{3}{8}$	17	10	28	13	55	16	14	0	0
$2\frac{1}{2}$	13	7	64	11	23	16	11	0	10
$2\frac{5}{8}$	4	11	33	10	63	14	12	0	2
$2\frac{3}{4}$	13	9	42	12	45	17	14	0 14	3
$2\frac{7}{8}$	5	8	25	14	70	16	15	0	0
3	8	9	38	11	54	15	13	0	2
$3\frac{1}{8}$	100	13	0	..	0	..	13	0	0
$3\frac{1}{4}$	..	..	..	..	..	..	..	0	6

These links are removed and tested. The results from this special testing have also been entered into the values of the tables. Therefore, it is necessary to consider these results somewhat in the light of values for the efficiency of the power-forging process, rather than entirely a value for strength of chain as it is issued for service.

THE PROVING OF CHAIN CABLE.

The value of the proof test for chain is universally recognized. All chain intended for any service, wherein the safety of human life depends upon its strength, is proved by an appli-

cation of a certain load which is usually about one-half of the required breaking load and about twice the maximum working load. The proof load is not a definite value but varies somewhat according to the particular requirements of the various societies and governments. It may vary from 50 to 70 per cent of the required breaking load. There is, however, a practical disadvantage in requiring a proof load much above 50 per cent of the breaking load, because the rate of elongation increases rapidly as the load passes this figure. Yet, a high proof load may, if it is to be applied only once during the life of the chain,

TABLE V.—ELONGATION OF STUD CHAIN UNDER PROOF LOAD.

Size of Chain, in.	Number of Tests.	Proof Load Applied, lb.	Elongation, per cent.
$\frac{3}{4}$	18	22 400	4.7
$\frac{7}{8}$	49	30 100	4.8
1	18	38 800	4.8
$1\frac{1}{8}$	60	48 500	4.7
$1\frac{1}{4}$	73	59 300	4.8
$1\frac{1}{2}$	45	84 000	4.7
$1\frac{3}{4}$	36	112 700	4.9
2	62	145 400	4.9
$2\frac{1}{4}$	94	182 000	4.5
$2\frac{1}{2}$	50	222 500	4.7
$2\frac{5}{8}$	49	244 200	4.6
$2\frac{3}{4}$	100	266 800	5.0
$3\frac{1}{4}$	50	367 000	4.9

be the better choice; this will depend upon the particular conditions. In the case of chain cable that is periodically annealed and proved, it is necessary to have the re-proving load reasonably low, in order to keep the length of the chain within the required limits during its life. The figures accepted as satisfactory for Government stud-chain cable are set at 60 per cent of the required breaking load for new chain and 50 per cent for chain that has been in service. As it has been shown that the true breaking loads are about 12 per cent above the required breaking loads, it is apparent that the figures 60 per cent and 50 per cent are in reality lower than they first appear.

While supporting the desirability and the necessity of the proof test, it should, nevertheless, be realized that a chain may pass the proof test satisfactorily and yet not be acceptable for service. This condition has been repeatedly observed when links, severely burned, would pass the proof test, but fail soon afterwards. It is, therefore, very important that competent inspectors examine each link of the chain after the proof test. Should a link show any defect, that in the inspector's judgment would be dangerous, it should unquestionably be replaced.

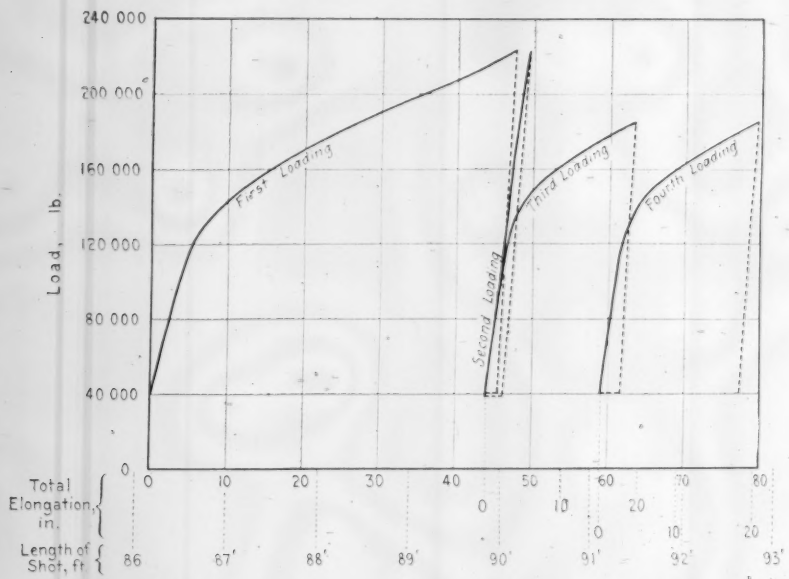


FIG. 9.—Load-Elongation Diagram of Shot No. 1277, 15-fathom, 2½-in. Wrought-Iron Stud-Chain Cable.

Tables and Discussions.—Table V lists elongations in percentages for new stud-chain shots under proof loading. The figures apply to 15-fathom (90-ft.) shots and the elongations are in percentages of the original length. The table is based on data from inspectors' reports of chain purchased on contract by the Government and on data obtained from chain manufactured at the Boston Navy Yard.

Table V shows that the average increase in length of a shot

of chain, as a result of proving, is 4.8 per cent. This figure is of value, in that a shot of chain can be manufactured to a certain length, so that after proving it will be the length required. At the Boston Navy Yard, shots of chain are manufactured 86 ft. in length. After proving, the requirement of 90 ft. in length is closely complied with.

Fig. 9 is a load-elongation diagram of a shot of $2\frac{1}{2}$-in. stud chain under proof loading, and illustrates the effect of annealing and proving on the physical properties of the chain. A new shot of chain, manufactured in the usual manner, was chosen for the test. It was annealed by heating to 950° C., holding it at that temperature for ten minutes, and air-cooling it. When placed in the testing machine, it was found that a 40,000-lb. load was required to free the shot of twists and excessive sag, so that the test was started at that load. Referring to Fig. 9, it is seen that a yield point is indicated near the 120,000-lb. load. Above this point the rate of elongation is rapid. The total elongation at full proof load, 222,500 lb., amounts to 48 in. After the first loading, the chain was removed from the testing pit and allowed to rest for thirteen days. The length of the shot at the start of the second loading is shown to be $1\frac{1}{2}$ in. shorter than the length previously taken at the end of the first loading. This apparent decrease in length was due to the fact that better bearing or contact surfaces existed between the links after the maximum load had been applied and then released to 40,000 lb. than in this case where the 40,000-lb. load only was applied to the chain. The curve for the second loading shows that the elongation is low if not negligible, for the length of the shot at the start of the third loading corresponds to the length of the shot at the start of the second loading. Prior to both the third and fourth application of the load, the chain was annealed in the same manner as before the first loading. The curves of the third and fourth loadings are similar to that of the first loading. They indicate that re-annealing removes all effect of the cold work evident during the second loading and reduces the yield point to its original value.

DISCUSSION.

Mr. Goldmark. MR. HENRY GOLDMARK. I should like to say a few words to give my experience with this same power-forged chain as made at the Navy Yard in Boston. In connection with my work as Designing Engineer on the Panama Canal, it was found necessary to secure about 75 sections of chain, each 100 to 150 ft. in length, of homogeneous quality and uniform strength. The links were made from iron bars 3 in. in diameter, each link being about 17 in. long and $10\frac{1}{2}$ in. wide, and of the standard U. S. Navy shape.

The chains were used in the so-called chain fenders in the canal locks, which serve to protect the lock gates from injury from vessels striking them. Each of the fenders, of which there are 24 in all, consists essentially of a series of vertical cylinders in the lock walls, by which a chain is kept stretched across the lock for checking the travel of a vessel in case it accidentally approaches a lock gate too closely.

When struck by a vessel the chain pays off under a definite stress, regulated by relief valves attached to the hydraulic cylinders. Hence the maximum load on the chain can be quite definitely determined. It is, of course, important to know the actual breaking strength of each chain section. With the hand-forged links commonly used, much difficulty was encountered in securing chains having an ultimate breaking strength as great as that specified by both the United States and British Navies, and there was great lack of uniformity in the several sections.

In the case of the open links without studs, which are used in those sections which pass over the sheaves in the machinery, the strength was considerably less than in the stud link chain, and there was less homogeneity. There were many rejections, although the specified requirements were somewhat reduced. The trouble lay, of course, entirely in the weakness and lack of conformity in the welds.

Before all the Panama chains were made, the process of power forging was perfected and used on the remaining sections. The improvement in the quality was very marked, the breaking

strength was much higher, and there was much greater uniformity. There were almost no rejections, and the appearance of the links was much better. It proved essential, however, to anneal all sections carefully. Mr. Goldmark.

Although it is claimed that similar processes have been used abroad, the officials at the Boston Navy Yard deserve much credit for developing the method with much perseverance and success. For large chains, it seems quite certain that hand forging will soon be entirely superseded.[1]

As an example of the important part which the character of the weld plays in determining the strength of a chain, reference may be made to certain of the anchor cables of the S. S. Leviathan (formerly the Vaterland of the Hamburg-American Line). These were made from bars 4 in. in diameter, but have a breaking strength only slightly greater than that of 3 or $3\frac{1}{4}$-in. cables, owing to the difficulty of securing sound welds on such heavy links, at least by hand power. These 4-in. cables are clumsy and expensive, with no counterbalancing advantages.

[1] A full record of all the tests is given in a paper by the writer, presented to the Western Society of Engineers in February, 1919, and printed in their Journal.

A NOTE ON THE CONSTITUTION OF CERTAIN TIN-BEARING BRASSES.

By William Campbell.

From the viewpoint of structure, the brasses and the bronzes can be divided into several distinct groups; but the limiting compositions of these various groups depend on the heat treatment.

The two simplest cases are those of the alloys in the cast state and after annealing. In the cast state the alloys are not in a state of chemical equilibrium; whereas in the annealed condition, especially after mechanical treatment, the alloys are generally in the stable condition.

The following table gives the limits of the various constitutents of the brasses and bronzes both in the cast state and after annealing:

	Tin, per cent.	
Bronze.	As Cast.	Annealed.
Alpha	0 – 5	0 – 11
Alpha plus eutectoid	5 – 26.5	11 – 26.5
Eutectoid plus delta	26.5 – 31.8	26.5 – 30
Brass.	**Zinc, per cent.**	
Alpha	0 – 32	0 – 36.5
Alpha plus beta	32 – 47	36.5 – 45.5
Beta	47 – 49.5	45.5 – 49
Beta plus gamma	49.5 – 60	49 – 60

When the brasses are compared with the bronzes, it is seen that the chief difference from the viewpoint of structure lies in the fact that in the brasses the beta constituent remains stable down to normal temperatures, whereas in the bronzes it breaks down in the neighborhood of 500° C. into a mechanical mixture of alpha and delta or the eutectoid.

During an examination of certain commercial brass castings and of Naval Brass castings it was found that while some of the alloys resembled Muntz Metal in that they consisted of a mixture of alpha plus beta, some of them had the structure of

bronze in that they consisted of alpha plus eutectoid. Another group consisted of alpha plus beta plus eutectoid.

All of these samples were made to the following specifications:

NAVAL BRASS CASTINGS.

Copper	60 – 65	per cent
Tin	0.5 – 1.5	"
Zinc	Remainder	
Iron, maximum	0.5	"
Lead, maximum	1	"
Aluminum, maximum	0.5	"

COMMERCIAL BRASS CASTINGS.

Copper, minimum	62	per cent
Zinc, minimum	30	"
Iron, maximum	0.75	"
Lead	1.5 – 3	"
Nickel or Tin	Remainder	

In order to determine the limits of composition between the three distinct types of alloys a study was made of the ternary diagram of copper, tin and zinc and the boundaries between the various fields: namely,

I Alpha
II Beta
III Alpha plus Beta
IV Alpha plus eutectoid
V Alpha plus Beta plus eutectoid

were determined approximately for the metal in the cast state. To do this, alloys weighing 50 to 100 g. were melted in clay crucibles under potassium cyanide and when thoroughly molten and mixed were allowed to cool within a larger crucible in air, because it was found that in this way the structure was comparable with sand castings of small size.

In order to determine the field boundaries of the various alloys in a state approximating equilibrium or at all events corresponding to castings which had been thoroughly annealed, samples were heated to 650° C., held there for two hours, and slowly cooled in the furnace. The results obtained are very similar to those of Hudson and Jones, who investigated the alloys within the limits of 50 to 70 per cent copper and 0 to 5 per cent tin, and gave a diagram representing annealed alloys

in a state of equilibrium which is attained after 24 hours annealing.

The alpha plus beta plus eutectoid area is approximately triangular and its corners occur at the following compositions:

As Cast.	Tin, per cent.	Zinc, per cent.	Copper, per cent.
(1)	4.5	37.5	58.
(2)	2.0	41.5	56.5
(3)	0.2	31.4	68.4
Annealed.			
(1)	4.0	39.0	57.0
(2)	1.4	43.6	55.
(3)	0.25	35.5	64.25

From this it will be seen that as the copper contents of the alloy increases from 56.5 per cent as cast, the amount of tin which will cause the alloy to change from the alpha plus beta condition into the alpha plus beta plus eutectoid condition decreases from 2 per cent to less than 0.5 per cent with 67 per cent of copper.

Similarly, with the annealed alloys, the amount of tin decreases with the increase in copper, but the amounts are much less. With 55 per cent copper, 1.5 per cent tin gives an alloy of the alpha plus beta plus eutectoid type. With 63 per cent of copper, less than 0.5 per cent tin makes the alloy pass from the alpha plus beta type into the alpha plus beta plus eutectoid type.

The physical properties of these two types of alloys are markedly different. The alpha plus beta type corresponding to Muntz Metal, Naval Brass, Tobin Bronze, etc., showed good tensile strength with an elongation of over 50 per cent, whereas the alloys of the alpha plus beta plus eutectoid type, showed physical properties comparable with Gun Metal.

The alloys of copper and tin and copper and zinc are of great industrial application. The bronzes, strictly speaking, consist of copper and tin while the brasses are composed of copper and zinc. They can both be classified according to their constituents. For example, alpha bronzes contain 0 to about 5 per cent of tin as cast or 0 to 11 per cent of tin in the annealed condition, as, for example, Sheet Gun Metal. Bronze consisting of alpha plus eutectoid contains from 5 to 26.5 per cent of tin as cast or 11 to 26.5 per cent tin when annealed. The hardness

increases with the amount of eutectoid c. p. Gun Metal and Bell Metal.

In the case of the brasses, the alpha metal contains 0 to 32 per cent of zinc as cast and 0 to 36.5 per cent of zinc in the annealed condition, as for example Rolled or Drawn Brass. Brasses consisting of alpha plus beta contain 32 to 47 per cent of zinc as cast or 36.5 to 45.5 per cent of zinc in the annealed condition. These are typified by Muntz Metal. Beta brasses contain 47 to 49 per cent of zinc as cast or 45.5 to 49 per cent of zinc when annealed, *e. g.*, solder. Beyond this point a third constituent gamma comes in and the metal becomes brittle.

In engineering work, while there are numerous brasses consisting of copper and zinc alone, when we examine the bronzes we find that they are rarely the binary alloys of copper and tin; for example, Gun Metal consists of, copper 88 per cent, tin 10 per cent and zinc 2 per cent, while most of the more common types of bronze contain varying amounts of tin and zinc.

When the brasses and bronzes are contrasted from the viewpoint of structure, the main difference is that in the brasses the beta constituent remains stable while in the bronzes it breaks down on slow cooling into a mechanical mixture of alpha and delta or the eutectoid at about 500° C. and this change is similar to the pearlite change or eutectoid in steel. It has long been known that small percentages of tin added to Muntz Metal cause the beta constituent to disappear and the eutectoid to take its place. Some fifteen years ago an example was encountered wherein two samples of Manganese Bronze of apparently the same composition showed very marked differences in physical properties. Under the microscope, one consisted of the normal alpha plus beta structure while the other was composed of alpha plus eutectoid. A beginning was then made to determine the amount of tin necessary to cause the change of the beta into the eutectoid and at the same time to determine the main fields of the copper-tin-zinc ternary diagram. It was soon found that this work required a great deal of time and only enough of it was completed to show that the Muntz Metal type of alloy can contain about 2 per cent of tin when the zinc was as high as 41 per cent without any signs of the transformation of the beta into the eutectoid, whereas when the zinc was in the

neighborhood of 34 per cent the beta was found to transform in castings containing 0.5 per cent of tin. This work was continued from time to time as opportunity allowed and numerous examples were found of Naval Brass castings and Commercial Brass Castings showing the transformation of the beta into the eutectoid.

In the fall of 1911, Hoyt took up the study of the copper-tin-zinc alloys at Columbia University and completed his work at the Royal College of Technology, Charlottenburg, and his results were published in 1913.

These show that the beta solid solutions of copper and tin and copper and zinc are isomorphous. The liquidus surfaces, the limit of saturation of the alpha solid solution and the eutectoid line were determined. His ternary diagram shows approximately the limits of the alpha, the alpha plus eutectoid and the alpha plus beta areas.

In 1915, the work was taken up by R. M. Banks in a thesis on the "Inversion of the Beta Constituent in Copper-Zinc-Tin Alloys," submitted in partial fulfillment of the requirements for the degree of Metallurgical Engineer, Columbia University. This work gave an approximation of the various fields of the diagram.

This was continued by Dr. G. Asahara on the samples in the cast condition and the alpha plus beta plus eutectoid area roughly determined. Figs. 1 and 2 show our results, as determined on samples weighing from 50 to 100 g. melted in clay crucibles under potassium cyanide and when thoroughly molten and mixed, allowed to cool within the larger crucible in air. The structures obtained were found to be very similar to those of small sand castings.

The alpha plus beta plus eutectoid area is approximately triangular and its corners occur at the following composition:

As Cast.	Tin, per cent.	Zinc, per cent.	Copper, per cent.
1	4.5	37.5	58.
2	2.0	41.5	56.5
3	0.2	31.4	68.4

The effect of annealing was studied by taking pieces of these alloys and heating them to 650° C. for two hours in an

electrical resistance furnace and then cooling very slowly in the furnace through the eutectoid range. In this way, alloys were obtained approximating a state of equilibrium or at all events corresponding to castings which have been thoroughly annealed followed by slow cooling. The result of this treatment is to narrow the alpha plus beta area while at the same time the alpha plus beta plus eutectoid area is moved over to the right. It is still triangular in shape and its corners occur at the following composition:

ANNEALED.	TIN, PER CENT.	ZINC, PER CENT.	COPPER, PER CENT.
1	4.0	39.0	57.
2	1.4	43.6	55.
3	0.25	35.5	64.25

Results of these annealing experiments are given in Figs. 3 and 4.

These results of annealing are very similar to those of Hudson and Jones whose boundaries for the alpha plus beta plus delta area is given by the dotted triangle *HGK*. For the preparation of these annealed samples I am indebted to Mr. Kempovsky.

Fig. 1 is the copper-tin-zinc diagram up to 32 per cent tin or delta and 60 per cent zinc or gamma, as cast. It seems most probable that the delta of the copper-tin series or Cu_4Sn and the gamma of the copper-zinc series or Cu_2Zn_3 form a single series of solid solutions, hence in the ternary alloys rich in both zinc and tin it is impossible to distinguish delta from gamma, and therefore areas VI and VII are given as delta or gamma, etc. The boundary line *a b* between the alpha area and the alpha plus eutectoid field runs from 5 per cent tin to 32.5 per cent zinc and is approximately correct. The line *c l* is the boundary between the two fields alpha plus eutectoid and delta or gamma plus eutectoid, and the alloys on this line show only the eutectoid, a mechanical mixture of alpha and delta or alpha and gamma. The line *f o p g* joins the delta point of the bronzes (31.8 per cent tin or Cu_4Sn) and the gamma of the brasses (60 per cent zinc or Cu_2Zn_3) as these two are supposed to form a single series of solid solutions.

Fig. 2 is an enlargment of the zinc-rich corner of Fig. 1. Alloys in the field *d m n e* consist of the single constituent beta. In the area *b K m d* we have two constituents, alpha and beta, and the alloys resemble muntz metal, tobin bronze or manganese bronze in structure and physical properties. The line *m K* divides the alpha plus beta and the alpha plus beta plus eutectoid fields and is approximately correct. Similarly, the line *l K* divides the alpha plus eutectoid and the alpha plus beta plus

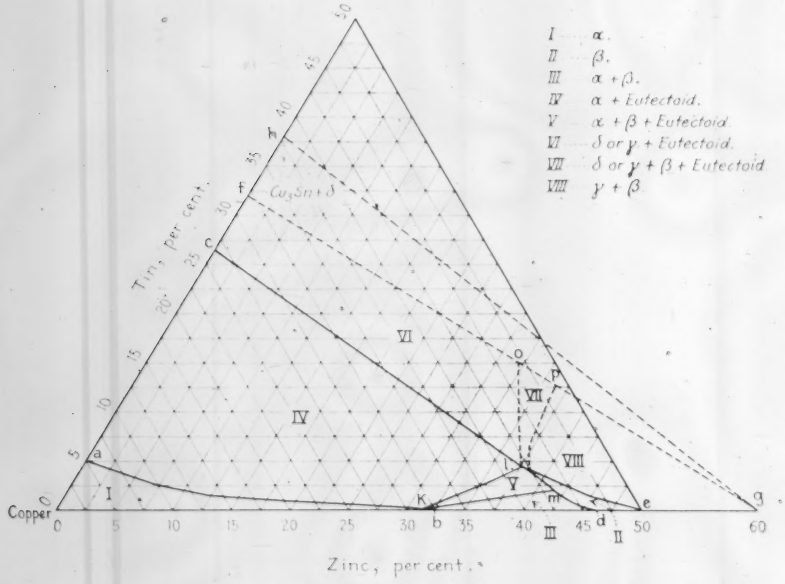


FIG. 1.—Copper-Tin-Zinc Diagram. As Cast.

eutectoid areas. The exact location of the point *K* has yet to be determined and it may be that the lines *l K* and *m K* will be found to coincide at about 67 per cent of copper.

The gamma plus beta plus eutectoid field, VII, is merely an approximation and many more alloys will have to be made before it can be definitely settled.

Fig. 3 gives the diagram for the samples annealed at 650° C. for two hours followed by very slow cooling in the furnace. The line *a b* now runs from about 11 per cent tin to 36.5 per cent

zinc and is curved. The alpha field is thus very much enlarged, giving a much wider range of composition for the copper-tin-zinc alloys showing a single constituent: *e. g.*, sheet metal and other cold worked material. The line *c l* dividing the alpha plus eutectoid and the delta or gamma plus eutectoid areas is approximately the same as in the unannealed alloys as was to be expected.

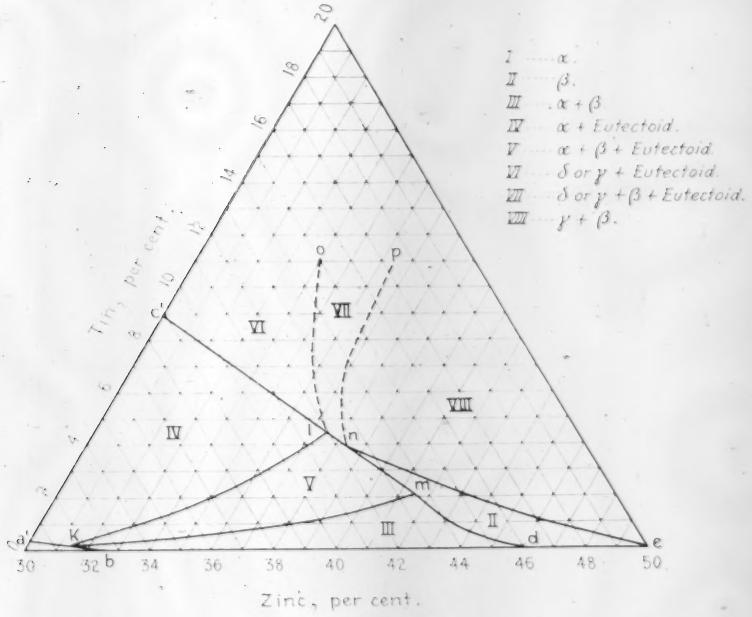


FIG. 2.—Copper-Tin-Zinc Diagram. As Cast.

Fig. 4 is an enlargment of the zinc-rich corner of Fig. 3. To this has been added the triangle *G H K* of Hudson and Jones, representing a state of equilibrium after 24 hours annealing at an average temperature of 425° C. It gives the alpha plus beta plus delta field and therefore embraces fields V and VII of our work, because the eutectoid is a mixture of alpha and delta. The line *a' b'* shows the boundary of the alpha field of Hudson and Jones and they have taken the limit of the copper-zinc solid solution alpha as 37.5 per cent instead of 36.5 per cent zinc

as given by Mathewson and Davidson. Taking this into consideration and the difference in the methods of annealing, the agreement between our results and theirs is as close as can be expected.

The beta field II has become much smaller and so has the alpha plus beta area III. This shows that annealing cast metal in these ranges may cause the precipitation of delta or gamma

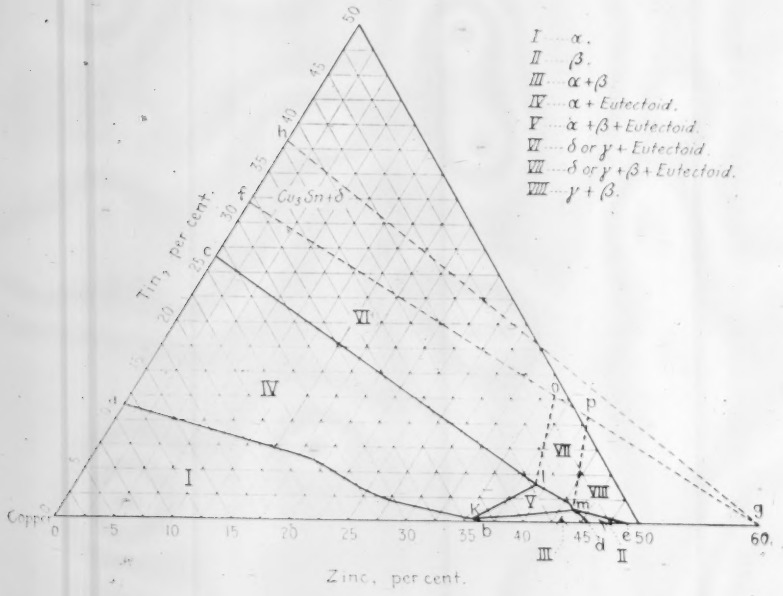


FIG. 3.—Copper-Tin-Zinc Diagram. Annealed at 650° C.

resulting in a marked loss of ductility. As before, the lines *o l* and *p m* are merely approximations and have yet to be definitely located as in the cast alloys in the unannealed state.

By comparing these four diagrams it will readily be seen that the small alpha area of the alloys in approximately the cast state is very much enlarged by annealing. Secondly, the alpha plus beta area is very much more restricted in the annealed samples. As cast, a brass with 41.5 per cent of zinc will hold 2 per cent of tin without causing a transformation of the beta, while an alloy with 31.5 per cent of zinc shows a transformation

of the beta if more than 0.25 per cent of tin is present. In the annealed alloys an alloy with 43.6 per cent of zinc will hold 1.4 per cent tin and still show no eutectoid, whereas an alloy with 35.6 per cent of zinc shows the eutectoid when approximately 0.5 per cent of tin is present. In other words, in both the cast and the annealed samples as the zinc is decreased the tin must be decreased proportionately if we wish to retain the alloys in the alpha plus beta condition. In spite of this fact most speci-

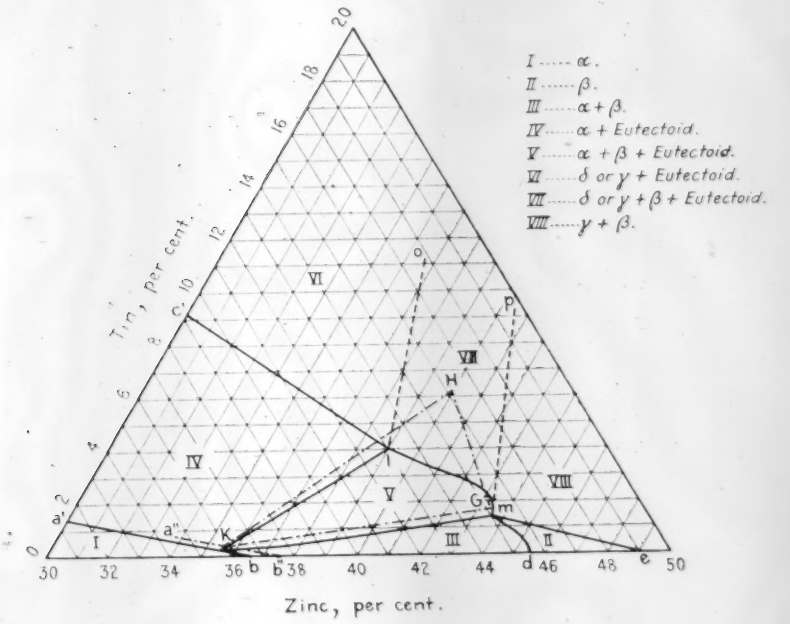


FIG. 4.—Copper-Tin-Zinc Diagram. Annealed at 650° C.

fications for Naval Brass and commercial brass castings allow a variation of at least 5 per cent in the copper content and give the limits of tin from 0.5 to 1.5 per cent. As has been shown above it would be better to write the limits for the zinc and the tin so that there would be no chance of obtaining an alpha plus eutectoid alloy or an alpha plus beta plus eutectoid alloy when an alpha plus beta type was desired.

In presenting these results it is realized that the work is

yet incomplete. From the scientific standpoint it is desirable to complete the diagram by determining more closely the other fields such as the delta plus eutectoid, the gamma plus beta plus eutectoid and the gamma plus beta areas. It is hoped that this can be done in time to present results to the Society at the next annual meeting.

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FATIGUE AND IMPACT FATIGUE TESTS OF ALUMINUM ALLOYS.

By W. A. Gibson.

In the past few years, aluminum has been used more and more as a means of reducing the weight of structures, principally in the automobile and airplane. This use has arisen chiefly because of its low specific gravity. However, in order to make full use of this low specific gravity, it is necessary that full use be made of the stresses which it is capable of withstanding.

The ordinary tensile properties of aluminum alloys are fairly well understood; but the fatigue, impact, and impact fatigue properties are but very little known. In close designing it is vitally necessary that these properties be known if the maximum possible reduction of weight consistent with safety is to be obtained.

Previous Work.

The single-blow impact properties of aluminum alloys have been rather thoroughly covered in two papers by E. H. Dix.[1] For that reason this paper will be limited entirely to fatigue and impact fatigue or repeated-blow tests. Three experimenters have reported previous work on the fatigue of aluminum. Elmendorf[2] gives a series of tests upon a cast commercial aluminum from which tests he obtained the formula

$$S = 48{,}000\ N^{-0.113}$$

in which S = maximum fiber stress in transverse loading and N = number of cycles to break. The analysis of the alloy is not given, but a stress-deformation curve furnished with the tests is very similar to that of the ordinary No. 12 alloy containing 8 per cent of copper. The common use of this alloy also makes it probable that this was the composition used.

[1] E. H. Dix, Jr., "Charpy Impact Test as Applied to Aluminum Alloys," Am. Inst. Min. & Met. Engrs., April, 1920.

E. H. Dix, Jr., "The Single Blow Notched Bar Impact Test as Used in the American Industry," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 720 (1919).

[2] A. Elmendorf, "Table and Charts Resulting from the Testing of Cast Aluminum on a White-Souther Rotary Testing Machine," *American Machinist*, Vol. 41, p. 811, (1914).

Merica and Karr[1] give a series of tests upon three alloys. Series A contains 8 per cent of copper; Series B, 12 to 15 per cent of zinc, 2 to 3 per cent of copper, remainder aluminum; Series C, 1.5 to 2 per cent of copper, 1.5 to 2 per cent of manganese, remainder aluminum. The equations obtained with these various alloys are as follows:

$$\text{Series A} \ldots\ldots\ldots\ldots S = 68{,}000\ N^{-0.132}$$
$$\text{Series B} \ldots\ldots\ldots\ldots S = 93{,}000\ N^{-0.159}$$
$$\text{Series C} \ldots\ldots\ldots\ldots S = 65{,}000\ N^{-0.139}$$

F. C. Lea[2] gives tests upon a number of alloys, mainly of the high-copper type such as the 12-per-cent copper, remainder aluminum, or of the copper-zinc-aluminum type alloy similar to the L-6 alloy developed by Rosenhain and Archbutt. In these tests considerable trouble was encountered due to bad castings. A large number of the tests were not carried to destruction as the purpose was, apparently, to find the stress at which the materials would stand approximately 5,000,000 reversals.

It is interesting to note that all previous published tests on aluminum alloys have dealt with the material in the form as cast, while the author has been able to find only one previous series of tests upon cast iron. This is shown in Curve C of Fig. 3, and was obtained from a paper presented before the Society by H. F. Moore and F. B. Seely in 1915.[3] The fact that the initial tests upon aluminum alloys have been made upon castings rather than upon worked parts as in ferrous alloys, is strongly indicative of the high hopes which have been and are entertained for this material and the reliance which is being placed upon it.

MATERIALS AND TREATMENT.

Thirteen different materials are reported in the following figures and tables. Of these, five are cast aluminum; one is cast iron; four are forged aluminum alloys of the duralumin type;

[1] Merica and Karr, *Technologic Paper No. 139*, Bureau of Standards.

[2] F. C. Lea, "Aluminum Alloys for Aeroplane Engines," Aeronautical Reprints No. 19, The Royal Aeronautical Society.

[3] H. F. Moore and F. B. Seely, "The Failure of Materials Under Repeated Stress," *Proceedings*, Am Soc. Test. Mats., Vol. XV, Part II, p. 437 (1915).

two are carbon steels, and one is a nickel steel. The analyses of these various materials are shown in Table I.

The physical properties as obtained by static tests are shown in Table II. The elastic limits were obtained by means of a dial type extensometer which measures to 0.0001 in. The yield points of steel and duralumin are well marked, but for cast aluminum alloys it is rather indefinite. In the values reported in Table II, it has been taken as the point where the deformation in a tension test was 0.0025 in. per inch. This is purely arbitrary but has been found to be approximately the amount which the average person can detect with dividers on a 2-in. bar.

TABLE I.—ANALYSIS OF METALS TESTED.

Sample No.	Material.	Composition, per cent.				
		Copper.	Iron.	Silicon.	Zinc.	
1901	Cast Aluminum Alloy	8.07	0.39	0.32		
1905	" " "	3.04	1.23	0.29	7.73	
1243	" " "	7.91	0.45	0.30	....	
2244	" " "	8.16	0.40	0.25		
2243	" " "	3.20	1.21	0.23	8.05	
		Copper.	Iron.	Silicon.	Magnesium.	Manganese.
1937	Forged Duralumin...	3.61	0.74	0.48	0.70	0.60
1596	" " ...	3.75	0.60	0.40	0.26	0.69
2223	" " ...	3.88	0.45	0.26	0.78	0.64
2213	" " ...	....	....	....	....	....
		Carbon.	Manganese.	Phosphorus.	Sulfur.	Nickel.
2187	Forging Steel.....	0.35	0.45	0.016	0.010	....
2214-*A*	Very Soft Steel.....	0.042	0.34	0.012	0.026	....
2278	Nickel Steel.....	0.246	0.76	.....	.....	3.63

The treatments given to the various materials are important in both the cast and the worked materials.

Sample No. 1901, which is a cast aluminum alloy containing approximately 8 per cent copper, was cast in sand using a pouring temperature of 1300° F. in the ladle just before pouring. The maximum furnace temperature attained was between 1400 and 1450° F. The shape of casting employed is shown by Fig. 2 (*a*). In the actual casting, a finish of $\frac{1}{8}$ in. on the diameter was allowed except in the tension bars, which were tested with the skin on. Adequate risers were used at each end of the bar. The pouring temperature of 1300° F. was adhered to in all of the cast materials.

Sample No. 1905 which, as shown by Table I, is an aluminum-zinc-copper alloy was cast in a manner exactly similar to that of sample No. 1901.

Sample No. 1243, which is an aluminum alloy containing approximately 8 per cent copper, was cast in an identical manner with sample No. 1901 except that a straight bar $1\frac{1}{8}$ in. in diameter was cast. The material under test in this sample, therefore, comes from the center of a $1\frac{1}{8}$-in. bar. These results are accordingly not the best which could be obtained from this material.

Samples Nos. 2244 and 2243 were cast in a similar manner

TABLE II.—PHYSICAL PROPERTIES.

Sample No.	Material.	Stress, lb. per sq. in.			Elongation in 2 in., per cent.	Reduction of Area, per cent.	Hardness No.		
		Elastic.	Yield.	Maximum.			Brinell.	Scleroscope.	Charpy.
1901	Cast Aluminum Alloy	.....	11 820	22 300	1 8	....	80	19	....
1905	" " "	.....	8 631	29 220	5 1	....	70	18	....
1243	" " "	.....	18 165	24 690	1 0	....	..	..	....
2244	" " "	8 620	13 490	24 860	2 3	....	74	15	....
2243	" " "	8 100	15 280	29 820	4 7	....	80	18	....
1937	Forged Duralumin	18 000	22 800	47 510	27 3	37 4	100	19	....
1596-*X*	" "	.....	14 000	38 460	19 7	35 9	..	..	....
2223-*A*	" "	.....	30 100	52 125	25 3	39 9	..	..	....
2223-*B*	" "	.....	27 000	52 075	21 3	34 8	..	..	....
2213	" "	13 000	19 000	47 000	18 2	28 6	83	19	....
2187	Forging Steel	70 250	74 250	98 000	16 3	54 9	227	30 5	37 6
2214-*A*	Very Soft Steel	34 000	36 200	46 600	38 5	79 5	74	11	....
2278	Nickel Steel	.....	121 400	130 600	17 3	66 4	262	36	57 5

to Sample No. 1901 except that the form into which they were cast is that shown by Fig. 2 (*e*). A finish on the diameter of $\frac{1}{8}$ in. was allowed in casting.

Sample No. 2187 was obtained from the Park Drop Forge Co. of Cleveland, Ohio. An analysis ingot was forged to a bar $1\frac{1}{8}$ in. in diameter. This was then sawed up into test pieces, heated to 1550° F. and quenched in cold water. The pieces were then annealed until a Brinell hardness between 200 and 230 was reached. In most cases this was obtained by a first reheating to 900° F. However, it was necessary to reheat a few of the bars a second time in order to bring them down to the desired hardness.

Sample No. 2214-*A* is a very mild steel which was obtained in the form of a hot-rolled rod $\frac{5}{8}$ in. in diameter. It was purchased in the open market in Cleveland and was tested as received.

Sample No. 2278 is nickel steel obtained in the form of a $\frac{5}{8}$-in. cold-rolled rod from the Franklin Automobile Co. of Syracuse, N. Y. Rods of the proper length were cut, heated to 1500° F. and quenched in Houghton No. 2 quenching oil. They were then reheated to 950° F. and allowed to cool in air.

Sample No. 1937 was poured into a cast-iron ingot mold,

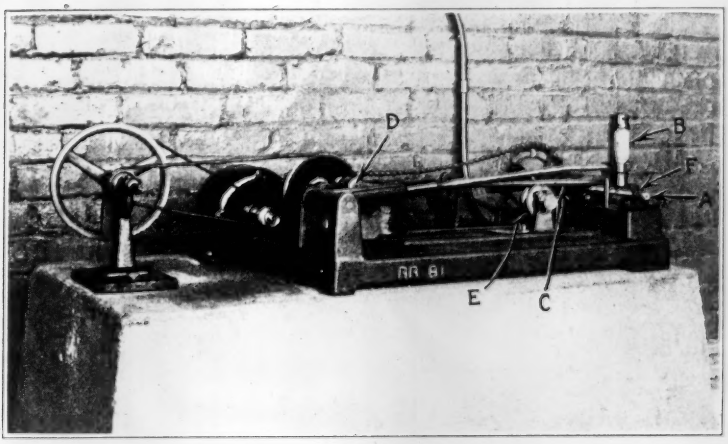
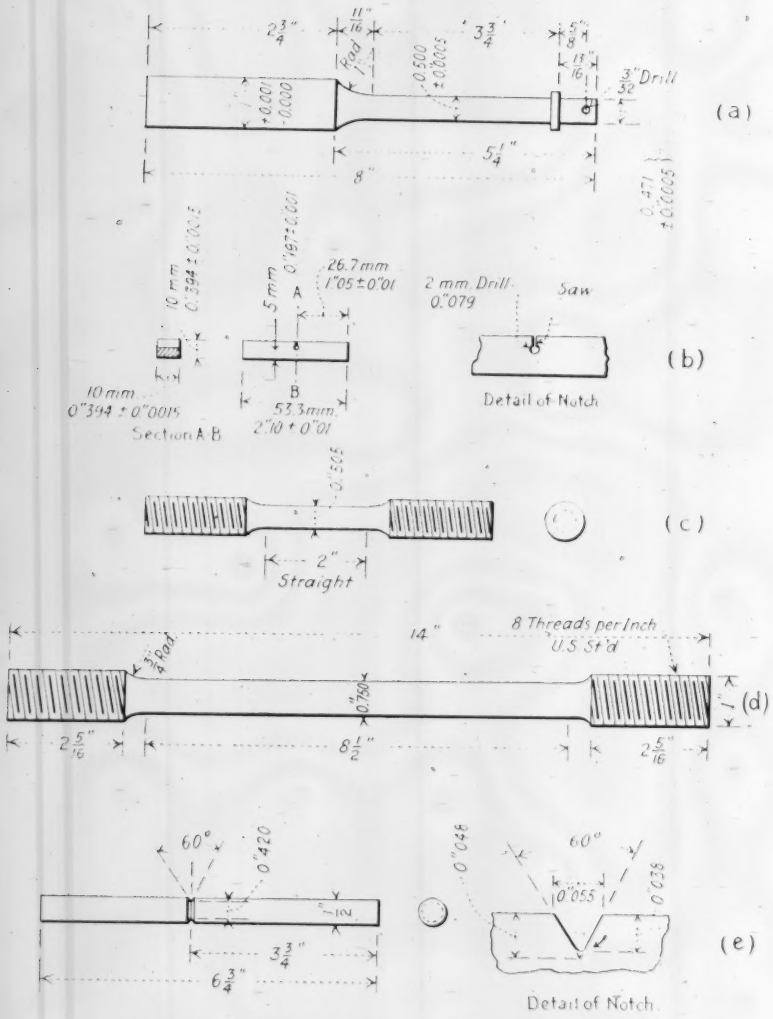


FIG. 1.—Stanton Type of Impact Fatigue Machine.

reduced approximately 50 per cent by hot rolling and then forged from a 2-in. square section to approximately the section shown by Fig. 2 (*a*) A finish on the diameter of $\frac{1}{8}$ in. was allowed. In this condition as forged, the bars were heated to 930° F. for one hour in nitre, quenched in cold water, reheated in oil at 300° F. for one hour and cooled in air. They were then machined to size shown in Fig. 2 and tested. The reheating at 300° F. was for the purpose of eliminating the aging effect which is common to a large number of aluminum alloys.

Sample No. 1596-*X* received the same working as the previous sample but was not heat-treated.



(a) Test Bar for White-Souther Fatigue Machine

(b) Charpy Impact Specimen

(c) Standard 0.505 Diam Test Bar.

(d) Modulus of Elasticity Specimen

(e) Impact Fatigue Test Bar.

FIG. 2.—Types of Test Specimen Used.

Sample No. 2223 received the same forging treatment. Two separate treatments were given this sample. Sample No. 2223-*A* was heated to 930° F. for one hour and water-quenched. The bars were then reheated at 212° F. for six days in order to give them an accelerated aging. Sample No. 2223-*B* after forging was heated slowly from 800 to 940° F. and water-quenched. They were then allowed to remain at room temperature until tested several weeks later.

Sample No. 2213 was heated for one hour at 920° F. after forging and quenched in Houghton No. 2 quenching oil. They were then aged for six days at a temperature of approximately 150° F. This latter temperature was not very closely controlled and may have varied from 100° F. to as high as 200° F.

TESTING METHODS.

The tension tests were made on an ordinary tension testing machine. In most cases a 10,000-lb. Olsen testing machine was used. Where the stress was expected to be over 50,000 lb. per sq. in., a 50,000-lb. Olsen testing machine was used. A White-Souther type of machine was used in all the fatigue tests. This is the same type as used by the three experimenters whose work has been referred to earlier in the paper.* The White-Souther machine uses a rotating test piece of either a cantilever or a beam type. In these tests the cantilever type was used. In some initial experiments considerable trouble was encountered due to the vibration of the weights. As soon as the machine was moved from a wooden to a cement floor, this trouble was eliminated. A speed of 1328 r. p. m. was maintained throughout all of the fatigue tests.

The impact fatigue tests were carried out on a Stanton type of machine. As this type of apparatus is not very common in America, it will be described somewhat in detail.

Referring to Fig. 1, *A* is the test bar shown in detail in Fig. 2 (*e*). This is supported on V-blocks $4\frac{1}{2}$ in. apart, so located that the groove shown in Fig. 2 (*e*) is midway between the supports and directly under the tup. This tup is pivoted as shown and through the action of the arm *C* and the crank *D* is alternately raised and let drop. The amount of drop is regulated by the location of the roller *E* and may be varied from 0.1 to 3.5 in.

by steps of 0.1 in. Between each blow the test bar *A* is rotated through 180 deg., so that the test consists of a series of blows alternating from one side of the test bar to the other. In order that these blows may always be upon the same point during any one test, the drive for the test bar is through a chain gear. A speed of between 100 and 110 r. p. m. was maintained in all tests.

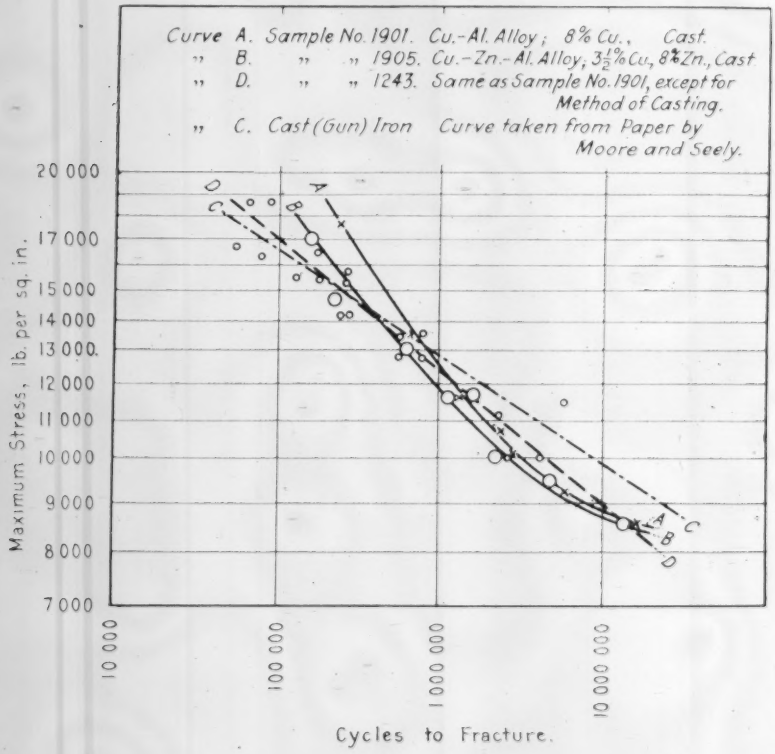

Curve A. Sample No. 1901. Cu.-Al. Alloy; 8% Cu., Cast.
" B. " " 1905. Cu.-Zn.-Al. Alloy, 3½% Cu, 8% Zn., Cast
" D. " " 1243. Same as Sample No. 1901, except for Method of Casting.
" C. Cast (Gun) Iron Curve taken from Paper by Moore and Seely.
Maximum Stress, lb. per sq. in.
20 000
17 000
15 000
14 000
13 000
12 000
11 000
10 000
9 000
8 000
7 000
10 000
100 000
1 000 000
10 000 000
Cycles to Fracture.

FIG. 3.—Showing Relation Between Number of Cycles to Fracture and Breaking Load in Fatigue Test.

The tup employed gives a static pressure of 5.46 lb. on the test bar when at rest. This weight is not standardized in the Stanton machine and it has usually been left to the discretion of various experimenters what weights to use. In the set-up shown in Fig. 1, a static pressure of 3.1 lb. is given by the hammer shown. A heavier hammer than that shown was used during these tests.

The various types of test bar used in obtaining the data are shown in Fig. 2. The tension specimens of cast material were tested as cast with the skin on; the tensile strengths are therefore somewhat higher than would have been obtained with the specimens used in the fatigue and impact fatigue tests.

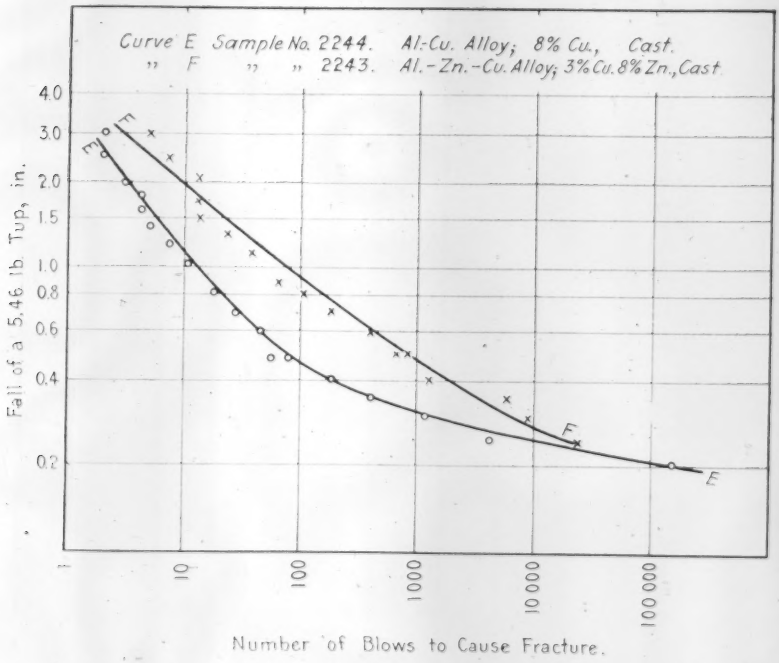


FIG. 4.—Showing Relation Between Number of Blows to Fracture and Height of Fall of Tup in Impact Fatigue Test.

TESTS UPON CAST MATERIALS.

In Fig. 3 are shown fatigue tests upon two types of aluminum-base alloys and upon cast iron. The tests upon aluminum were made in a White-Souther type of machine using a rotating cantilever as a test piece.

Fig. 4 gives the results of impact tests upon two types of cast aluminum alloys. The fall of the tup in inches has been plotted as ordinates, since it is believed that this type of test

is purely comparative and that any attempt to transfer values to stress in pounds per square inch would lead to considerable errors. For those who desire to know approximately through what nominal stress ranges the various tests have been run, Table III has been prepared showing the fiber stress caused in several materials by various heights of fall. These data were obtained by making a slow transverse test on a Stanton type of

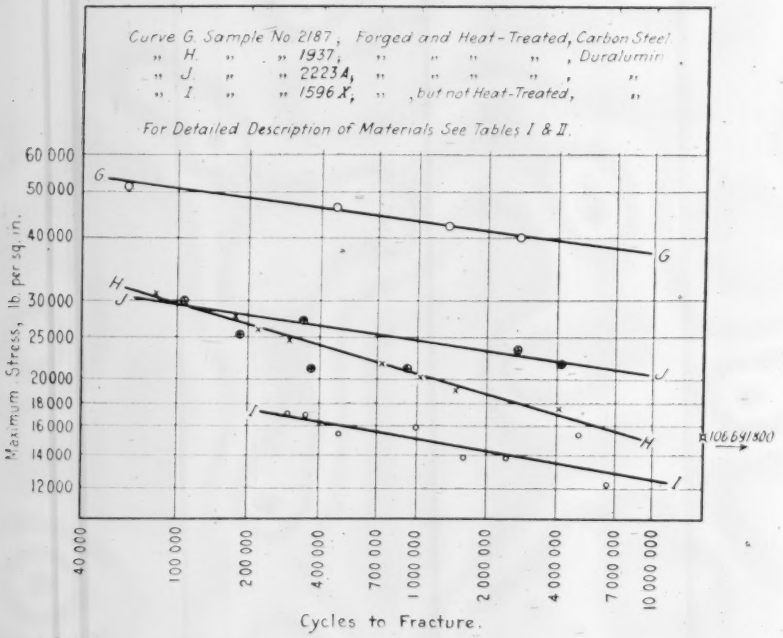


FIG. 5.—Showing Relation Between Number of Cycles to Fracture and Maximum Stress in Fatigue Test.

bar supported in a manner exactly identical with that in the Stanton testing machine. The amount of work done when various loads had been applied was measured and from this and the amount of work done by the hammer at various heights of fall the pressure on the test bar corresponding to each height of fall was computed. The stress was then computed by means of formulas found in any book on strength of materials.

This method is open to serious objections in that the amount of deflection obtained on static and on dynamic loading is not the same for most materials and also to the fact that stresses as computed by the formula $M = SI/c$ are admittedly incorrect when notched effects enter in as they do in the present case. Recognizing these objections, Table III is nevertheless presented as an example of the results that would ordinarily be obtained by a machine designer in estimating stresses in such sections.

Fig. 5 shows fatigue tests upon various types of forged duralumin both in the condition as forged and as heat-treated, and also upon a heat-treated carbon steel such as is commonly used in connecting rods.

Fig. 6 shows impact fatigue tests upon forged duralumin.

TABLE III.—FIBER STRESSES CAUSED BY VARIOUS HEIGHTS OF FALL OF TUP.

ALL STRESSES IN POUNDS PER SQUARE INCH.

Test.	Material.	Fall of 5.46-lb. Tup, in.					
		3.0	2.0	1.0	0.7	0.5	0.3
A	Cu-Al Alloy	.....	.....	38 700	33 700	30 700	25 600
B	Cu-Zn-Al Alloy	.....	48 700	39 400	36 200	32 100	25 600
C	Forged Duralumin	78 800	71 600	53 300	.....	37 300	.....
D	Mild Steel	96 000	94 800	76 000	.....	59 000	.....

upon the same carbon steel illustrated in Fig. 5, upon a nickel alloy steel and upon a very mild steel.

TYPES OF FRACTURES.

In the Stanton type of test the fracture begins in the outer fibers in the bottom of the groove directly under the point of application of the blows. It gradually works inward until finally failure occurs in tension at the neutral axis. This neutral axis is indicated by a small line due to the final break which occurs in tension. This tension is applied with the outer fibers as a fulcrum. The neutral axis as indicated by the final break is in most cases very close to the center of gravity of the cross-section, but in some few cases has been fully twice as far from one edge as the other. In all true fatigue breaks the section is,

with the exception of this final tension break, perpendicular to the axis of the piece and has the smooth brittle appearance characteristic of most fatigue breaks.

In the White-Souther type of test, which employs a gradually changing stress from a maximum in tension to an equal maximum in compression varying symmetrically about the point

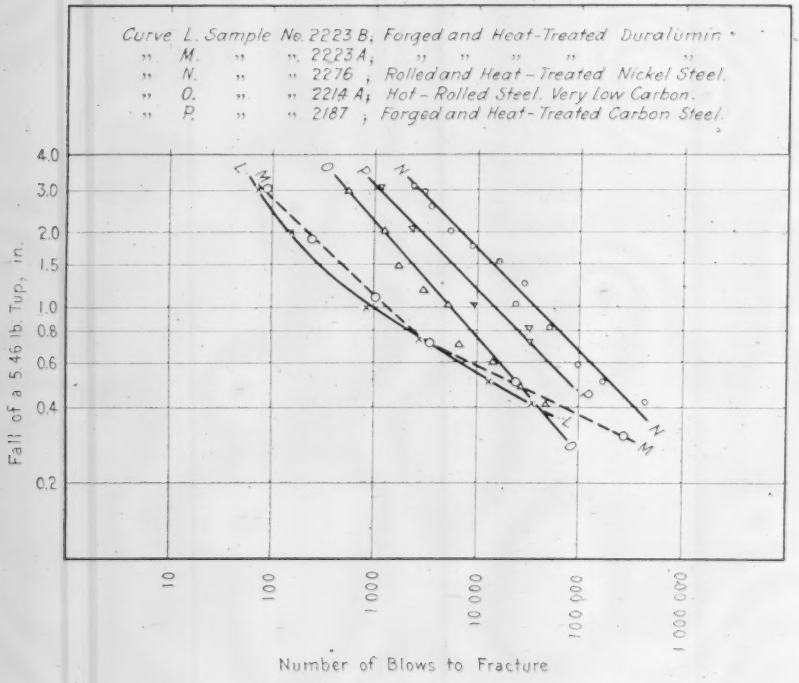
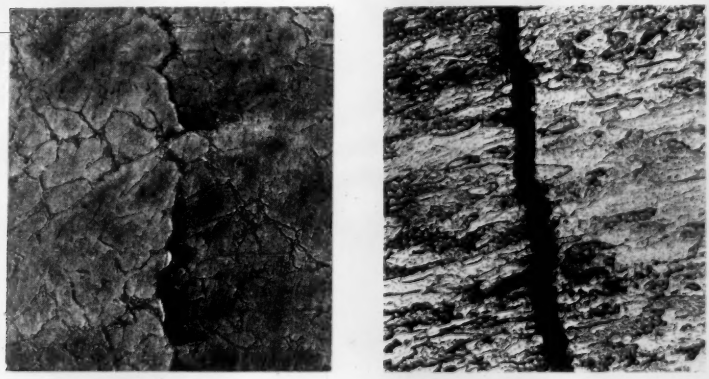


FIG. 6.—Showing Relation Between Number of Blows to Fracture and Height of Full of Tup in Impact Fatigue Test.

of zero stress according to a sine law, the fractures over the greater part of the section were perpendicular to the axis of the test piece. Apparently, however, the final break in most cases was by tension; so that the broken bar showed the characteristic fatigue fracture over approximately three-fourths of the section and a tension fracture over the other one-fourth. This tension fracture extends in the form of a sector from the periphery of the

test piece nearly to the center. This type of fracture was nearly universal in the forged duralumin specimens. It occurred to some extent in the steel specimens and was almost totally lacking in the cast specimens.

No elaborate attempt has been made to follow microscopically the path of fracture, but Figs. 7 (*a*) and (*b*) are given to show the path followed in cast and in forged material respectively. These photographs were taken from a longitudinal section of broken test bars after the broken parts had been squeezed together in a vise. The photographs were taken as near the



(*a*) Cast Aluminum, Sample No. 1901, Bar D.

(*b*) Forged Aluminum, Sample No. 1937, Bar D.

FIG. 7.—Cross-Sections of Cast Aluminum and Forged Aluminum (× 50). Etched with Very Dilute HNO_3 with Trace of HF.

periphery of the test piece as possible. It will be seen that in the cast material the fracture follows the network of $CuAl_2$, while in the forged material the fracture follows through the grains. In both of these the fractures are of the same type as would be observed in a tension test.

In the forged duralumin samples the specimens were tested in such a way that fracture occurred perpendicularly to the long axis of the grains. It is possible that the path of fracture might have been intercrystallin if the loading had been such as to make it parallel to the long axis of the grains. In practically

all forged machined parts, however, forging and loading occurs in such a manner that if fracture takes place at all, it will occur perpendicularly to the long axis of the grains. For this reason it is believed that tests in the other direction are not worth while.

GENERAL DISCUSSION.

Basquin[1] and later many others noted that the fatigue of metals followed an exponential law which may be stated as

$$S = CN^a$$

in which S = fiber stress, N = number of cycles to break, and C and a = experimentally determined constants. This equation, when plotted to logarithmic coordinates, gives a straight line. At the time when Basquin presented his paper on this subject, very few fatigue tests had been run for periods of more than 10,000,000 cycles. It has since been shown that there are numerous exceptions to the above exponential law when low stresses and extremely long periods of life, such as are encountered in high speed machinery of the present day, are used. In these latter cases the values extrapolated by means of the exponential formula proposed by Basquin give values of stress which are well on the side of safety.

This is also true of aluminum base alloys as is shown by curves A and B of Fig. 3. In fact, with the cast alloys this departure from the exponential law seems to take place relatively closer to the maximum stress than is the case with steel. Another case where a departure occurs from the exponential law is in the last point of curve H, Fig. 5, which gives tests upon a forged and heat-treated duralumin. From extrapolation from the previous tests we would have expected failure in this case to have occurred after about 8,500,000 cycles. Failure actually occurred after 106,691,800 cycles. This departure from the exponential law was not observed in curve D of Fig. 3. However, it will be noted that these results are somewhat erratic, as would be expected from material taken from the very center of a casting, and it is possible that these erratic results have masked some slight departure from a straight line on logarithmic paper.

[1] Basquin, "The Exponential Law of Endurance Tests," *Proceedings*, Am. Soc. Test. Mats., Vol. X, p. 625 (1910).

A complete study of the microscopic mechanism of fatigue failure is far beyond the scope of this paper, but the author believes that such a study would yield considerable information on aluminum alloys which would be of immense benefit in the automobile and airplane industries.

The impact fatigue tests as shown by Figs. 4 and 6 need very little comment. It will be observed that, for the higher loadings and quicker breaks, a straight line relation is obtained on logarithmic paper in this type of test as with the ordinary fatigue test; also that for the lower loadings and longer periods of test the curves depart from the straight line law on logarithmic paper the same as in the fatigue tests. This furnishes an interesting speculation in the case of curves *M* and *O* of Fig. 6. For the higher loads which approximate more closely the conditions as obtained in the static tension tests or in single blow impact tests curve *O*, which gives results upon a very mild steel, shows results much superior to those of curve *M* which gives results upon a forged and heat-treated duralumin. However, the reverse is true at the lower stresses, which are still much above those encountered in ordinary practice. It is a question if the same might not be true in the case of the other materials used.

The tests were not continued further because of the limitations of this type of machine. With the tup hitting directly on the test piece, the notch becomes so deformed after a certain number of blows that the outside edges bear against each other, thus making the results inaccurate. This could probably be remedied by means of a jig, but this addition was not applied in these experiments.

As pointed out by H. F. Moore,[1] there are two ways of comparing materials in fatigue:

1. By comparison of the nominal fiber stress under which failure occurs for a given number of cycles of stress.

2. By comparison of the number of cycles of stress causing failure at some given nominal fiber stress.

The two methods yield quite dissimilar numerical results from the same test data. The second method does not lend itself readily to comparison of materials of different densities; and

[1] H. F. Moore "Some Fatigue Tests of Nickel Steel and Chrome-Nickel Steel," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 206 (1919).

partially for that reason the author believes that the first method is the proper one to employ in comparing the fatigue of aluminum alloys with that of ferrous alloys. In addition to the greater ease of comparing two materials of different specific gravities, the first method is one in which practically all comparisons are made in static tests, that is, two materials are compared according to the stresses which they will stand. This may be stated in another manner. When we buy a car, for example, we always consider how long the car will last. In the ideal case each part would be so loaded as to make the car the same as Oliver Wendell Holmes' "One Hoss Shay," which ran for one hundred years and then dropped to dust. The average life of an automobile may be considered as approximately five years. The number of miles per year of a pleasure car will average about 5000, although in many cases 10,000 miles is reached. The number of revolutions of the engine per mile is about 2500 which will give a connecting rod 62,500,000 alternations of stress at the load which is encountered in a motor. In an ideal case, therefore, a connecting rod will be so designed as to just stand the stress of a piston stroke repeated 62,500,000 times. Of course, a rather large factor of safety enters in regardless of the material used, but this is the process which is followed in the design of machine parts and is, therefore, the most logical one to follow in comparing tests intended to determine the suitability of materials for such parts.

Table IV gives the stress which will cause failure at one million, ten million and 100 million revolutions for various materials. These values are taken from Figs. 3 and 5.

As an example of the way in which materials of different specific gravities should be compared, let us take sample No. 2187, which is a forged and heat-treated carbon steel, and sample No. 2223-*A*, which is a forged and heat-treated aluminum alloy of the duralumin type. The ratio of the specific gravities of these alloys is 2.7. This would mean that in order for the steel specimen to be of the same weight as the aluminum alloy specimen, its cross-section would have to be reduced to $\frac{1}{2.7}$ that of the latter, and that its extreme fiber stress under the same transverse load would be $2.7^{\frac{3}{2}}$ or 4.44 times as great as that of the aluminum

specimen [1] Referring to Fig. 5, it is seen that in order for the duralumin (No. 2223-*A*, curve *J*) to last 4,000,000 cycles, the stress must not exceed 22,000 lb. per sq. in. while for the steel (No. 2187, curve *G*) the stress must not exceed 39,000 lb. per sq. in. for the same length of life. The ratio of these stresses is 1.77 and less than the value of 4.44 necessary for equal weights. In this particular case, therefore, it would be concluded that, weight for weight, in transverse loading the heat-treated aluminum is superior.

Attention is called to the differences between curves *H*, *J*, and *I*, Fig. 5. All of these are the same type of material, namely, duralumin. The working is the same and the difference between them is due solely to the treatment they have received. The

TABLE IV.—MAXIMUM FIBER STRESS TO CAUSE FAILURE.

STRESS IN POUNDS PER SQUARE INCH.

Revolutions.	Sample No.				
	1901	1905	1243	2187	1937
1,000,000	12 500	11 900	12 300	42 000	21 000
10,000,000	8 800	8 600	9 000	38 000	16 000
100,000,000	.....	.....	.....	.....	15 000

treatment of duralumin as developed by Wilm[2] consisted of quenching in water from about 930° F. Wilm, as well as many later experimenters, observed that the properties of this duralumin were not fixed after this treatment, but that the hardness and tensile strength increased while the elongation decreased. More recently it has been found that this aging can be hastened considerably by heating at a high temperature for some time. It is to this long accelerated aging given to the bars tested from sample *J* that its unusually good properties are attributed.

[1] In transverse loading such as has been employed in obtaining the data submitted in this paper the stress varies with the cube of the dimensions if similar sections are assumed. That is $S \propto \frac{1}{bd^2}$ or for round specimens, $S \propto \frac{1}{d^3}$. The area varies as the square of the dimensions.

[2] A. Wilm, "Metallographic Investigations of Aluminum Alloys Containing Magnesium." *Metallurgie* Vol. 8, p. 225 (1911).

CONCLUSIONS.

A sharp distinction should be drawn between fatigue tests made upon materials as cast and those as forged.

In cast aluminum alloys, the properties are very much affected by the care taken in molding, melting and pouring. On account of the high shrinkage of these alloys this care is much more necessary than with ferrous castings.

There are not sufficient data upon the fatigue properties of cast iron at hand to warrant any definite conclusions.

In the forged materials the ferrous alloys of either carbon or nickel steel are much superior to the aluminum alloys when the comparison is made volume for volume. When the comparison is made on the basis of weight for weight, the aluminum alloys are equal if not superior to the ferrous alloys. There is a possibility that in the impact fatigue tests at stresses usually encountered in machine parts, the forged aluminum alloys might surpass certain types of steel even when the comparison is made volume for volume. This is not thoroughly established.

DISCUSSION.

MR. P. D. MERICA.—I want to offer comment on only one phase of this very interesting paper that Mr. Gibson has given us, and that is the relation of the tension test results on his different classes of alloys to the results that he has obtained with the White-Souther machine. From Fig. 3 of his paper it will be observed that there is only a very slight difference between the maximum stresses withstood at one million or ten million alternations for the different alloys; at most, there is a difference of 1000 lb. per sq. in. between the results on alloys Nos. 1901 and 1905. In Table II it is observed that the difference between the proportional limits of these two alloys is relatively great. In alloy No. 1905, for example, the yield point is given as 8631 lb. per sq. in.; alloy No. 1901, as 11,820, and in alloy No. 1243, the yield point is given as 18,165 lb. per sq. in. The difference between the yield points of alloys Nos. 1905 and 1243 is almost 100 per cent, yet the difference in resistance to alternating stresses is very slight—only 10 per cent. These results are in entire agreement with those which Mr. Karr and myself published last year before this Society,[1] in which even greater divergence was observed. We tested an alloy containing 2 per cent of copper and 1 per cent of manganese, of which the yield point was approximately 5000 lb. per sq. in. in comparison with No. 12 alloy, of which the yield point was approximately 12,000 lb., and found that the difference in safe stress of these two alloys at ten million alternations was only approximately 1000 lb. per sq. in. **Mr. Merica.**

It appears that the resistance of these alloys to fatigue stresses does not depend upon the same ultimate properties of the materials as do their tension tests properties, and I should be very glad to hear Mr. Gibson's explanation of this fact.

The same thing is noticed with reference to hardness and tensile strength; it is known that the hardness of cast aluminum alloys, as measured by the Brinell test, bears no essential relation to the tensile strength. A hard alloy may have a low tensile strength, and a soft alloy, a high tensile strength.

[1] Merica and Karr, "Some Tests of Light Aluminum Casting Alloys: The Effect of Heat Treatment"; *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part I, p. 297 (1919).

Mr. Comstock.

MR. G. F. COMSTOCK (*by letter*).—I was much interested in Mr. Gibson's paper, not only for the valuable information it gives, but also as a check on our results along one of the lines he

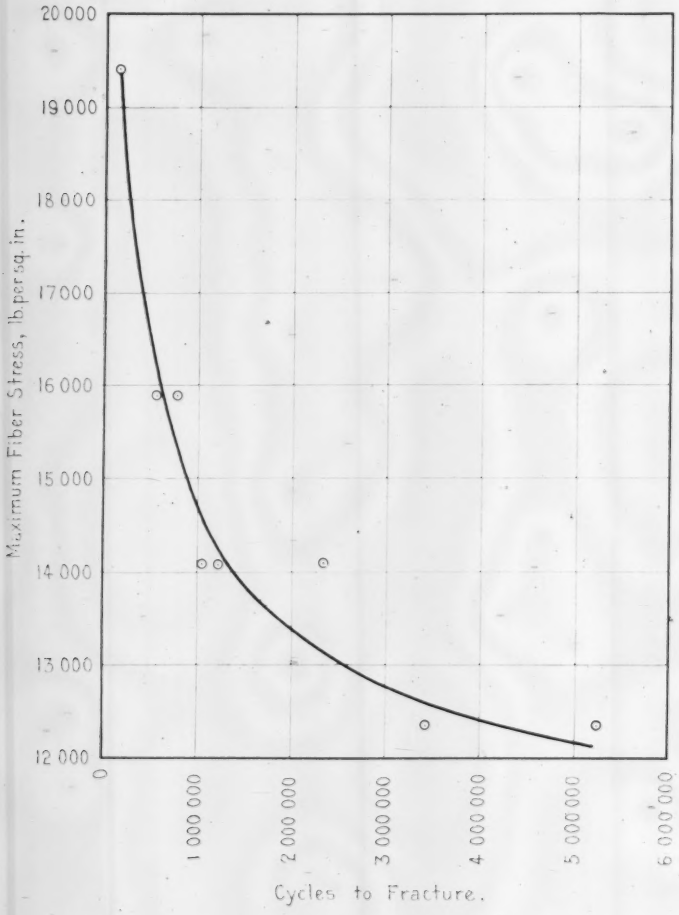


FIG. 1.—Stress Endurance Curve From White-Souther Tests of Aluminum Alloy with 8 per cent copper, half-chill cast.

covered. Possibly it would be worth while to give these few results of ours as a discussion. They are the outcome of some tests of an aluminum alloy with 8 per cent copper made in the

usual way on a White-Souther endurance testing machine. The alloy was cast in half-chill molds, about $1\frac{3}{8}$ in. in diameter and 1 ft. long, and the castings were machined to the standard size and shape for this test, as given by Mr. Gibson. The machining was accurate within the limits given on his diagram, and the testing machine ran fairly quietly and with only very slight vibration. The test bars all appeared sound, and the results were in good agreement with each other for this test. The results are tabulated below, and are plotted in Fig. 1, the scale of which is not, however, logarithmically divided, as is the case with Mr. Gibson's curves. Mr. Comstock.

MAXIMUM FIBER STRESS, LB. PER SQ. IN.	REVOLUTIONS ENDURED.
19 400	118 800
15 900	539 900
	777 600
	1 049 900
14 100	1 213 300
	2 340 200
12 350	3 448 800
	5 245 600

An inspection of the curve shows that for an endurance of about one million revolutions, or cycles, this alloy would stand a maximum fiber stress of about 14,500 lb. per sq. in. The results are somewhat higher than those reported for this cast alloy by Mr. Gibson, but when it is considered that his bars were cast entirely in sand, while ours were half-chilled, the difference is easily understood.

Possibly our results may be of some interest in connection with this paper as showing the benefit obtained by partially chilling this alloy, and also indicating the results that might be expected from castings of thinner section, which would solidify faster even though cast in sand.

MR. W. A. GIBSON (*Author's closure, by letter*).—Our observations confirm Mr. Merica's exactly. We have been able to find no relation whatever between the stress-deformation diagram as determined by an extensometer measuring to 0.0001 in. and the fatigue life of the material. In Mr. Francke's paper presented before the Society at this annual meeting,[1] he Mr. Gibson.

[1] See p. 372.—ED.

Mr. Gibson.

describes a method of making much closer measurements upon the deformation than any previously made. It may be possible that with such extra sensitive measurements some relation between the failure of various constituents, as determined in the tension test and the fatigue life, may be made.

I am also in hopes that some light upon the subject of fatigue failures may be obtained through microscopic examination of the mechanism of the failure.

The data obtained by Mr. Comstock is interesting and forms a valuable addition to the paper. That his results are somewhat higher than those obtained from bars cast entirely in sand is to be expected. The same effect can be observed in curves *A* and *D* of Fig. 3 in the paper. While the material used in obtaining both these curves was cast in sand, that of curve *A* was cast $\frac{5}{8}$ in. in diameter while that of curve *D* was cast $1\frac{1}{8}$ in. in diameter. It will be observed that the material of curve *A* is superior to that of curve *D*.

THE VOLUME-MOISTURE RELATION IN SAND AND A METHOD OF DETERMINING SURFACE AREA BASED THEREON.

By Roderick B. Young and William D. Walcott.

We are all more or less familiar with the fact that the space occupied by a given weight of fine aggregate is related in some way to the moisture contained by that aggregate. A sand ordinarily occupies more space when moist than when dry. In the course of an investigation undertaken to ascertain the bearing that this might have on the problems of proportioning concrete mixtures it was discovered that this phenomenon was related to the "surface area" of the aggregates involved.

Perhaps it would be well to define the terms "surface area," "bulking," "sand," and "dust" as used in this paper. The "surface area" of an aggregate is the summation of the surface areas of its individual particles—these particles being considered spheres, equal in volume to that of the actual particles. The investigations of Edwards[1] and others have shown that both the strength and water requirements of a concrete mixture are related rather definitely to the "surface area" of the aggregates used. Surface area is therefore used in proportioning concrete mixtures as a measure of the cement requirement of an aggregate.

When a sand increases in volume because of an increase in its moisture content, it may be said to "bulk." Bulking is expressed quantitatively as a percentage or ratio.

"Sand" is used in its commonly accepted sense: namely, a fine aggregate derived from a natural source all of which will pass, when dry, a screen having circular openings $\frac{1}{4}$ in. in diameter.

"Dust" as here used means that very fine material in a sand which will pass a No. 150 sieve.

The tests described in this paper were carried out by the

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II (1918). *Canadian Engineer*, Nov. 2, 1919, pp. 487-490.

authors in the laboratories of the Hydro-Electric Power Commission of Ontario as a part of an extended research being conducted there into the problem of concrete proportioning.

The materials used in these tests were sands which had been submitted to the laboratory in the course of its routine examination of aggregates. They came from sundry localities in Ontario and elsewhere—localities quite dissimilar geologically. Most, though not all, would be classed as good concrete sands.

Mechanical analyses were made of each sand from carefully prepared samples taken by the method of quartering. The sieves used were a perforated plate having $\frac{1}{4}$-in.-diameter openings and Tyler's Nos. 6, 10, 20, 35, 65 and 150. Grain counts were carried out on each size of separation for a representative sand from each locality and from these counts and the specific gravity, the surface area was obtained using the formula

$$A = 236.1 \sqrt[3]{\frac{n}{s^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where A = surface area in square feet per 100 lb., s = specific gravity of the sand, and n = number of grains per gram in any size of separation.

This method of obtaining surface area is essentially the same as that described by Edwards and uses the basic assumption, before noted, that the individual particles of sand are spheres. The surface area for any size as determined by the above formula is called the "unit area" for that size.

The increase in volume resulting from additions of moisture was obtained indirectly by determining the weight per cubic foot of the material first dry and then moist. Both $\frac{1}{8}$ and $\frac{1}{4}$-cu.-ft.-capacity cubical measures were used at different times. The measure was filled by means of a cylindrical shell, open at both ends.[1] This was placed in the measure, filled with the sand under test and slowly withdrawn. The capacity of the cylinder being slightly greater than that of the measure, an excess of material remained in the latter when the cylinder

[1] Cloyd M. Chapman, "The Testing of Sand for Use in Concretes," *Engineering News*, Feb. 5, 1915, p. 306.

was removed. This excess was struck off with a straight edge. Several determinations were made on each sand and the results averaged. It was found that the method gave concordant results.

To obtain sands of different degrees of moisture a predetermined amount of water was added to the dry sand and thoroughly worked into it by kneading.

Knowing the weight per cubic foot of the sand both dry

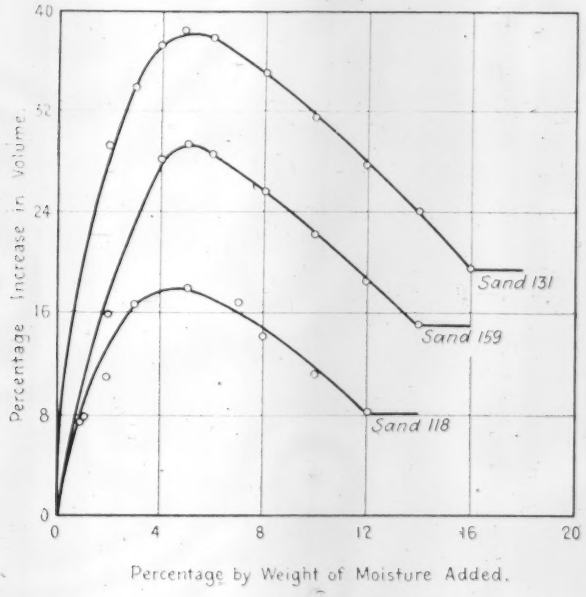


FIG. 1.—Relation between Moisture Content and Bulking in Sand.

and moist, the percentage increase in volume due to the added moisture was calculated from:

$$P = \frac{W_1 (1 + r) - W_2}{W_2} \times 100 \quad \ldots\ldots\ldots\ldots (2)$$

where P = per cent increase in volume, r = ratio of water added to weight of dry material, W_1 = weight per cubic foot of dry material, and W_2 = weight per cubic foot of moist material.

Fig. 1 shows the percentage increase in volume obtained in this manner for three sands: a fine, a medium and a coarse. The mechanical analyses of the same sands are shown in Fig. 2. These curves are representative of those obtained throughout this investigation.

A study of these tests revealed the interesting fact that the maximum percentage increase in volume, or bulking, is related to surface area. When plotted against surface area the points

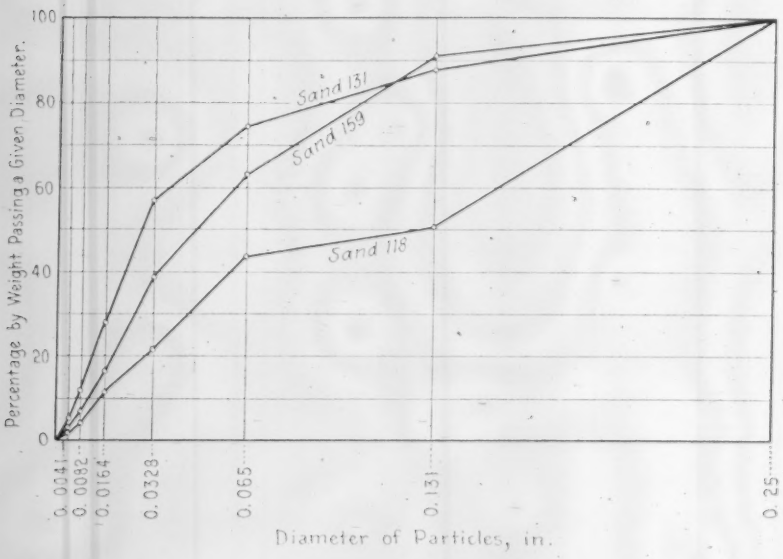


FIG. 2.—Mechanical Analyses Showing Range of Sand Used in the Investigation.

fall approximately on a straight line (Fig. 3). The equation of this straight line is

$$A = 40.6\,x + 180 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

in which A = surface area in square feet per 100 lb. and x = maximum increase in volume in per cent.

It may seem odd that the relation between bulking and surface area is independent of the percentage of water used to cause it. This would not be so were it not for the varying dust

contents of the sands. Fig. 4 shows a relation between bulking and surface area for one, two and three per cent additions of water. However, to show this relationship it was necessary to plot only results from sands having approximately equal dust

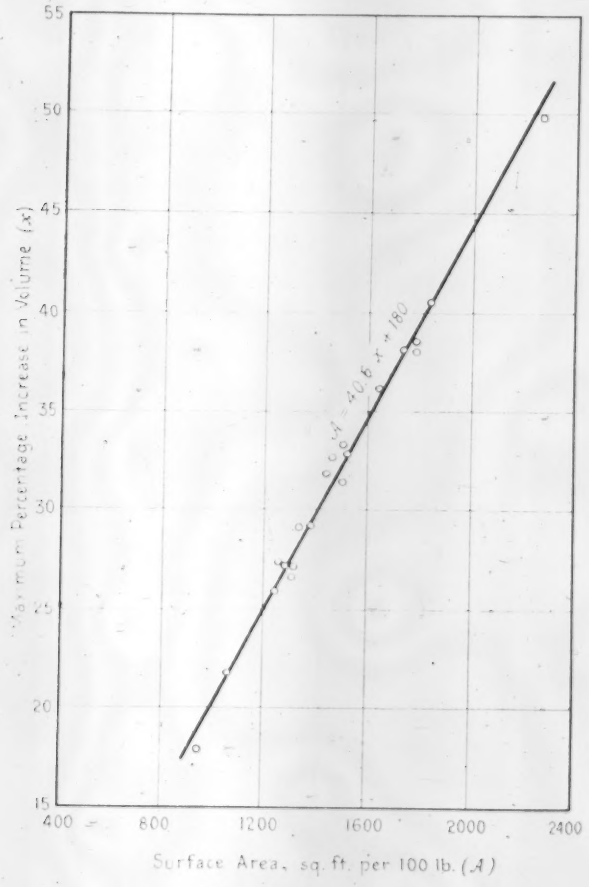


FIG. 3.—Relation between Surface Area and Maximum Bulking for Graded Sands Embodying Results Shown in Table I.

content. Other sands of different dust content would not conform to these curves.

Any dust contained in a sand will commence to absorb moisture as soon as water is added. This absorbed water takes little

or no part in the bulking phenomenon. It is the moisture in excess of that absorbed by the dust that causes changes in volume. Sands of equal surface area but containing different

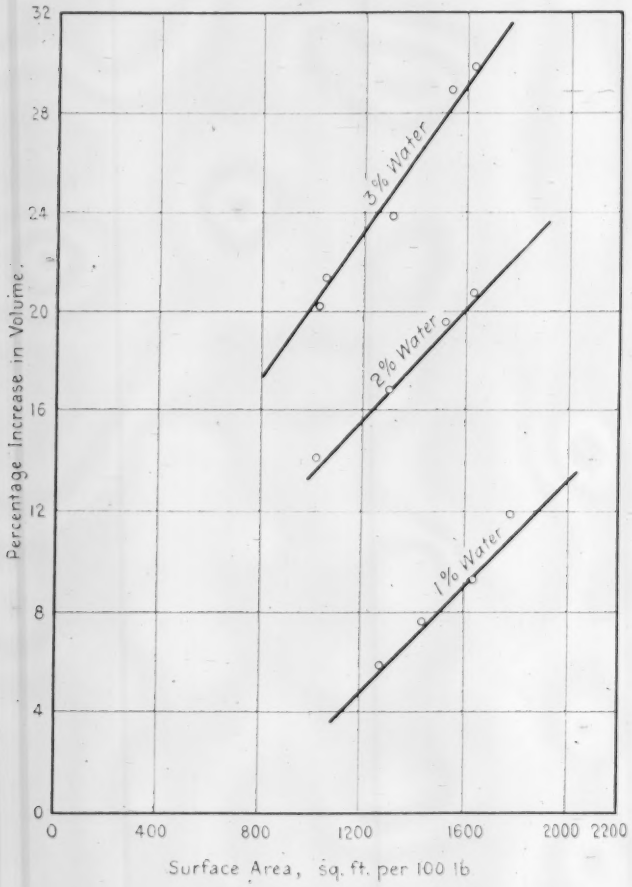


FIG. 4.—Relation Between Surface Area and Bulking for Different Moisture Content.

percentages of dust will bulk differently for the same percentage additions of water up to nearly the point of maximum bulking. At that point the variable effect of different dust contents is compensated for.

Experiments were also carried out upon sands having particles of uniform size. These sands were all prepared from one material by sieving it into its different sizes. Volume-moisture studies were then made on each size. These experiments also showed maximum bulking to be related to surface area. But it was found that this relation did not follow the same law as with graded aggregates. It was found that sands coarser that that passing the No. 6 sieve did not increase in volume

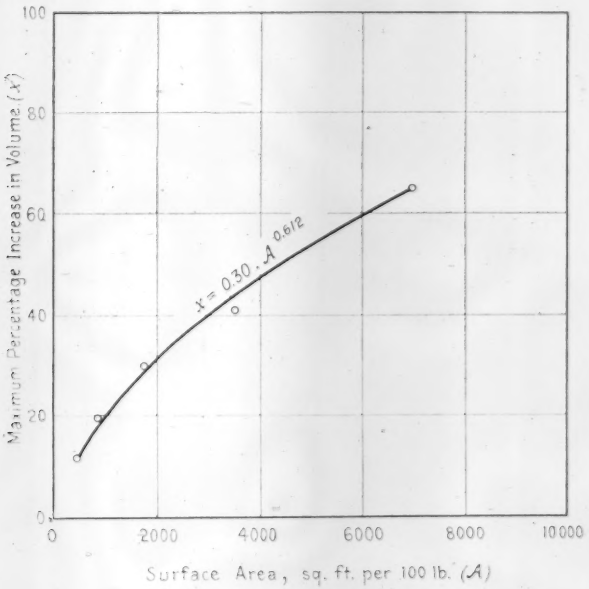


FIG. 5.—Relation Between Surface Area and Maximum Bulking for Sands of One Size.

with additions of moisture. It is thought that the reason for this is that the weight of the particles in these large sizes is sufficient to overcome the separating effect of the film of water surrounding the moistened particle. This explanation has not as yet been tested out experimentally.

Fig. 5 shows the relation between maximum bulking and surface area for these "one-size" sands. This relation is expressed by the equation

$$x = 0.30\, A^{0.612} \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where x = increase in volume in per cent and A = surface area in square feet per 100 lb.

A few experiments were made with mixtures of sand and gravel. Only one sand and one gravel were used but these

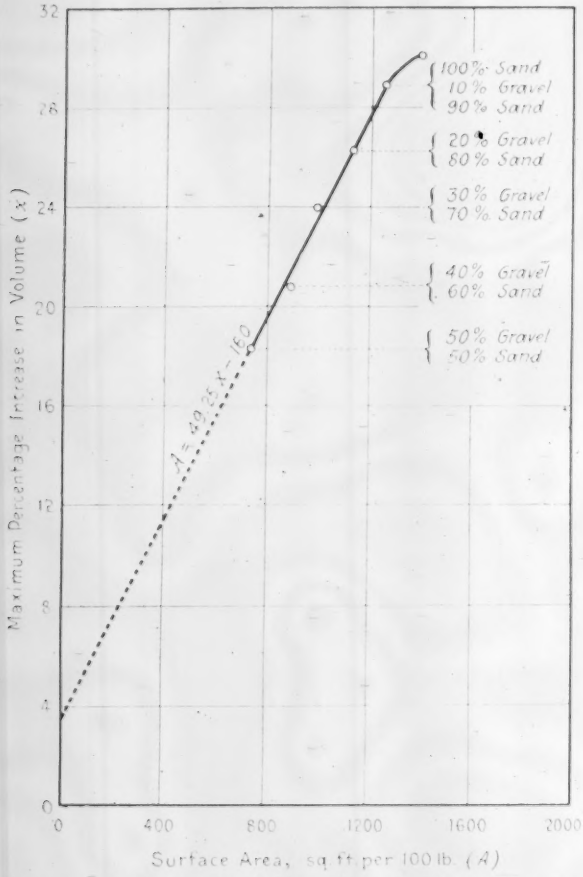


FIG. 6.—Surface Area - Bulking Relation for Mixtures of Sand and Gravel.

were mixed in different proportions. Here also a relation between bulking and surface area was found. Successive additions of gravel decreased the percentage of maximum bulking in the same ratio as it decreased the surface area. Fig. 6 illustrates the results of these few tests.

It is at once apparent that if the laws indicated by Figs. 3 to 6 inclusive are general, the maximum bulking of sand or of a sand and gravel mixture could be determined if its surface area was known; conversely its surface area could be determined if its percentage of maximum bulking was known. It is evident, however, by the behavior of "one-size" materials that these relationships are not perfectly general since the large-size particles take no part in the bulking phenomenon.

An experimental study of the limitations within which the conclusions hold have shown that the following is approximately true:

1. Extremely coarse sands, sands in which over 60 per cent by weight will not pass the No. 10 sieve, give results higher than those obtained by mechanical analysis. Sands of these characteristics usually have surface areas less than 1000 sq. ft. per 100 lb. They will usually be detected immediately by an experienced observer.

2. Extremely fine sands, sands in which 50 per cent passes the No. 65 sieve, give results lower than those obtained by mechanical analysis. The sands are really "one-size" materials and usually contain a high percentage of dust. They have surface areas in excess of 2000 sq. ft. per 100 lb. As in the case of the coarse sands they can usually be detected by examination.

Dust, when present in excess of seven or eight per cent, affects the accuracy of the results to some extent. For percentages lower than this, the effect of the dust is compensated for by the adoption of the point of maximum bulking.

Most sands acceptable for concreting purposes fall within the limits stated. This being so, the relationship between bulking and surface area has two very valuable applications in the science of concrete proportioning:

1. Knowing the surface area and the moisture content the changes in volume in the aggregate can be determined and proportions corrected accordingly.

2. Knowing the maximum increase in volume of a sand due to contained moisture, the surface area of that sand is at once obtainable.

While the first of these is important, it is not the subject of this paper and will not be elaborated upon. The second will be taken up at some length.

A method of obtaining the surface area of an aggregate which is both simple and rapid can be based on this relationship between the maximum bulking and surface area.

The weight per cubic foot of the sand to be tested is first determined dry and again after the addition of different percentages of moisture. The additions found to be best are four, five and six per cent of the dry weight of the aggregate; the maximum bulking usually occurring in this range, except for coarse sands free from dust when it may occur at as low as three per cent. The weight per cubic foot with the lowest percentage of moisture is first obtained; the last two percentages of moisture are then obtained by adding in each case the necessary extra water. The loss of moisture by this procedure has been found to be negligible. Applying successively Eqs. 2 and 3 to these results gives the surface area per 100 lb.

The equipment required is simple. That used by the writers consisted of a $\frac{1}{8}$-cu.-ft.-capacity cubical measure, a $\frac{1}{4}$-in. sieve to separate the fine and coarse aggregates, a small platform scales, and minor incidentals such as scoop, straight edge, glass graduate, etc. This apparatus may be varied somewhat to suit circumstances or the whims of the user without affecting the results.

Compared with the combined mechanical analysis and surface area calculations, the method is the acme of simplicity. It is rapid, inexpensive, requires a minimum of equipment and skill to carry out, and can be made to give accurate results.

Table I shows results obtained by both methods. Here are tabulated concrete sands having, as is evident from their surface areas, a wide variation in grading. The maximum difference between their surface areas as determined by sieve analysis and grain counts and as determined by the bulking test is approximately 3.7 per cent while the average difference is only 1.798 per cent. This degree of accuracy is within the probable error of the sieve-analysis method.

The bulking test does not agree with the standard method for obtaining surface area with very coarse sands, very fine sands or with sands high in dust. This has already been touched upon. Table I shows a number of such sands and the results obtained using both methods. It is thought by the authors to

be extremely likely that the surface area determined by the bulking test may be a better measure of the concrete-making properties of the sand than the values obtained from the sieve analysis.

The bulking method has one weak point and that lies in

TABLE I.—COMPARISON OF RESULTS OBTAINED BY MECHANICAL ANALYSES AND BULKING METHODS OF DETERMINING SURFACE AREA OF SANDS.

Sand No.	Source.	Maximum Bulking, per cent.	Surface Area, sq. ft.		Difference.	
			Mechanical Analyses.	Maximum Bulking.	Sq. Ft.	Per Cent.
106–1	Niagara Falls, Ont.	33.1	1515	1524	+ 9	+ 0.59
106–2	"	31.5	1494	1460	−34	− 2.28
106–5	"	32.7	1454	1508	+54	+ 3.71
118	Buffalo, N. Y.	18.0	945	911	−34	− 3.60
128	Nipigon, Ont.	21.7	1054	1062	+ 8	+ 0.75
130	High Falls, Ont.	38.1	1734	1727	− 7	− 0.40
131	"	38.5	1777	1734	−43	− 2.42
136	Nipigon, Ont.	25.9	1238	1232	− 6	− 0.48
137	"	29.2	1324	1366	+42	+ 3.17
141	"	33.6	1500	1545	+45	+ 3.00
143	"	40.7	1805	1830	+25	+ 1.39
149	Niagara Falls, Ont.	31.9	1436	1476	+40	+ 2.79
150	"	27.4	1256	1292	+36	+ 2.86
154	"	26.7	1299	1264	−35	− 2.70
155	"	36.1	1631	1647	+16	+ 0.98
159	"	29.3	1368	1370	+ 2	+ 0.14
161	Nipigon, Ont.	27.2	1273	1285	+12	+ 0.94
178	Havelock, Ont.	33.5	1513	1540	+27	+ 1.78
183	York, Ont.	27.3	1304	1289	−15	− 1.15
184	"	49.7	2264	2200	−64	− 2.83
					Average..	1.798
	COARSE SANDS.					
106–L1	Crushed Rock	21.6	717	1057	+ 340	+47.40
107	Niagara Falls, Ont.	28.2	1145	1325	+ 180	+15.72
129	Nipigon, Ont.	24.6	1003	1179	+ 176	+17.55
151	Niagara Falls, Ont.	23.3	866	1126	+ 260	+30.07
	FINE SANDS.					
106–4	Niagara Falls, Ont.	40.6	2079	1828	− 251	−12.05
134	Nipigon, Ont.	40.2	2420	1812	− 608	−25.12
144	Nipigon, Ont.	41.3	2446	1857	− 589	−24.05
157	Niagara Falls, Ont.	37.9	2888	1719	−1169	−40.04

its basic test—the one for the weight per cubic foot. This test is more subject to the personal equation of the operator than is the sieve analysis. It is believed that the rodding method of determining the weight per cubic foot—the method the Society is now considering for adoption as standard—would to

a large extent overcome this drawback. Before the rodding test could be used it would be necessary to establish the proper equations linking surface area and maximum bulking; the equations given in this paper only hold for the methods described.

The presence of mica in a sand introduces an interesting problem. Any considerable quantity alters the specific gravity of the material (the number of grains per gram) and hence the unit areas for the different sizes of separation. These unit areas will depend to some extent on the quantity of mica present so that surface areas calculated from them do not give values comparable to similarly graded sands free from mica. The bulking test has been found to give the better value in such cases.

In conclusion, we should like to point out that the tests here presented seem to bear out the contentions of Edwards and ourselves that surface area must be taken into account in any method of proportioning concrete mixtures. It is the opinion of the authors that this bulking of particles occurs in concrete mixtures and that a study of the bulking phenomenon in concrete and its relation to grading of the aggregates as measured by their surface area will throw much light on some of our present difficulties in determining a satisfactory method of proportioning concrete.

EFFECT OF HYDRATED LIME AND OTHER POWDERED ADMIXTURES IN CONCRETE.

By Duff A. Abrams.

Introduction.

There is a keen interest in engineering circles at the present time in the effect of powdered admixtures in Portland cement concrete. Many types of inert admixtures have been used designedly or due to their presence in the aggregate. The use of sands containing silt and crushed stone containing dust are usual examples of powdered admixtures. The so-called sand-cements are only another phase of the same subject. The use of hydrated lime in quantities up to 5 or 10 per cent of the weight of the cement has gained considerable vogue due to the feeling that it improved the workability of concrete, or increased the strength and water-tightness. Published tests may be found which appear to support the above conclusions. However, it will be seen below that more thorough tests show the error of these statements with reference to the strength and workability of mixtures usually used for structural purposes. Published data on this subject are generally inconclusive and conflicting due to lack of scope in the tests, or to confining the investigations to briquette tests of sand mortars. Water-tightness was not studied in this investigation.

Studies of the effect of admixtures on the strength and other properties of concrete have been under way in this laboratory for 4 years. This report is confined to powdered admixtures which are essentially inert in the presence of water and cement, as contrasted with liquids or soluble materials. While the major portion of the tests were made with hydrated lime, 17 other materials were also used, in order to determine the general effect of inert powdered admixtures.

The concrete materials were of commercial quality. Most of our studies were made on compression tests of 6 by 12-in. concrete cylinders; some investigations included also tension and compression tests of mortar. An important feature was the

wear tests of concrete made in the Talbot-Jones rattler. Bond tests were made in one series. Studies of evaporation and absorption were made on concrete containing hydrated lime and other admixtures.

The concrete was mixed by hand, each specimen being made from a single batch. The quantity of admixture was generally based on the volume of the cement in the batch and was an addition to rather than a replacement of the cement. Test pieces were stored in damp sand until the day of test, unless otherwise noted. The average values given in the tables and diagrams are generally based on 5 tests made on different days; in many instances 10 or 15 tests were made. The tests covered concretes of a wide range of mixes, consistencies, size and grading of aggregates, etc. Tests were made at ages of 3 days to $1\frac{1}{2}$ years; specimens are on hand for test up to 5 years.

This report covers six different investigations, and includes about 20,000 tests. The work was done as a part of the experimental researches in the properties of concrete and concrete materials being carried out through the cooperation of Lewis Institute and the Portland Cement Association.

OUTLINE OF TESTS.

The six series of tests in which powdered admixtures were used, may be characterized as follows:

Series 58 and 59, Tests of Sand and Slag Cements;

Series 100, Effect of Consistency on the Strength of Cement Mortars;

Series 104, Effect of Hydrated Lime on the Bond and Compressive Strength of Concrete;

Series 114, Effect of Hydrated Lime on the Strength and Wear of Concrete;

Series 130, Effect of Powdered Admixtures on the Strength and Wear of Concrete.

Series 58 (1916).—Tension and compression tests of mortar and compression tests of concrete were made at ages ranging from 7 days to 1 year, using cements with which sand or granulated blast furnace slag, in quantities up to 50 per cent by weight were mixed prior to final grinding. This series included about 2000 tests; see Fig. 11.

Series 59 (1916).—Compression tests were made no 1320 2 by 4-in. cylinders of 1 : 3 mix at ages of 7 and 28 days, using sands of 9 different gradings and the same cements described under Series 58. See Fig. 12. It should be noted that these cements were different from those in the later investigations; in practically all the later tests the powders were *added* to the cement in the batch. In two of the minor series (100 and 104) the admixture *replaced* cement at the time the concrete was mixed.

Series 100 (1917).—A special study was made of the effect of the consistency of mortars using different percentages of hydrated lime, kieselguhr, kaolin, powdered limestone and slag. In this series the admixtures replaced equal volumes of cement. The consistency varied from dry to very wet. Compression tests were made on 4550 2 by 4-in. cylinders at ages of 7 days, 28 days, 3 months, and 1 year; see Fig. 10.

Series 104 (1918).—Included parallel compression and bond tests of 1 : 5 concrete at ages of 7 days to 1 year. Hydrated lime was used as an admixture *replacing* cement up to 50 per cent of the volume of cement in the original mix. This series comprised 450 tests.

Series 114 (1918).—This was our first comprehensive investigation of the effect of hydrated lime on the strength of *concrete*. The hydrated lime was *added* to the batch up to 50 per cent by volume of cement. The consistency was varied from what we term "relative consistency" 0.90 to 2.00; the mix from 1 : 9 to 1 : 2 by volume; and the size of aggregate from 14-mesh sand to 1½-in. aggregate. Compression tests of 6 by 12-in. concrete cylinders were made at ages of 7 days, 28 days, 3 months, and 1 year; specimens are on hand for 2 and 5-year tests. In one group the curing condition of the concrete was varied in order to determine the effect of hydrated lime on the strength of concrete stored in damp sand for different periods followed by air storage. (See Table IX and Fig. 9). Wear and compression tests of concrete were carried out for 0, 10 and 33 per cent hydrated lime, using a 1 : 4 mix with 10 different aggregate gradings. (See Table XI). This series includes 3420 6 by 12-in. cylinders and wear blocks.

Series 130 (1919–20).—In this investigation many of the features of Series 114 were repeated. Most of the tests were made with high calcium hydrated lime; in one group high magnesium lime and 17 other powdered materials were used. (See Tables III, XIII–XV.) The mix varied from 1 : 9 to 1 : 2; consistency from dry to very wet (relative consistency 0.90 to 2.00); size of aggregate from 28-mesh sand to 1½-in. graded aggregate. In general powdered admixtures were used in quantities up to 50 per cent of the volume of the cement.

Compression tests of 6 by 12-in. cylinders were made at ages of 3, 7 and 28 days and 3 months; the 1-year tests are not due. Wear tests were made on concrete blocks at age of 3 months, with mixtures ranging from 1 : 4½ to 1 : 2½, using hydrated lime up to 33 per cent. In this series, a special effort was made to study the effect of admixtures on the plasticity or workability of the concrete by means of the slump test. This series included about 7500 tests.

TABLE I.—TESTS OF CEMENT.

Tests were made in accordance with the methods of the American Society for Testing Materials.

MISCELLANEOUS TESTS.

Cement, Lot No.	Admixture, per cent by weight.	Used in Series.	Fineness Residue on 200-mesh Sieve.	Normal Consistency, per cent by weight.	Time of Setting.				Soundness Test over Boiling Water.
					Vicat Needle.		Gillmore Needle.		
					Initial. h. m.	Final. h. m.	Initial. h. m.	Final. h. m.	
3641	.....	58 – 59	21.2	23.5	1 30	5 15	3 30	5 40	O. K.
3642	10 (sand)[1]	"	23.2	23.0	1 30	5 15	3 30	5 40	"
3643	20 "	"	23.5	23.0	2 00	5 45	4 15	6 40	"
3644	30 "	"	23.8	23.0	2 00	5 45	4 15	6 40	"
3645	40 "	"	25.0	23.5	2 40	8 00	4 30	8 00	"
3646	50 "	"	25.3	23.0	2 40	7 35	4 30	7 45	"
3647	10 (slag)[1]	"	21.1	23.0	1 45	5 40	4 15	5 50	"
3648	20 "	"	22.0	23.0	3 00	6 15	4 40	7 15	"
3649	30 "	"	22.0	23.0	3 00	6 15	4 40	7 15	"
3650	40 "	"	22.5	23.0	3 05	7 20	5 00	8 00	"
3651	50 "	"	22.0	23.0	3 30	8 00	5 00	8 30	"
4035	.....	100	17.4	23.0	3 50	8 15	5 30	8 50	"
4066	.....	"	20.6	22.0	3 40	6 20	4 00	6 40	"
4013	.....	"	0	34.0	0 56	4 55	2 15	5 15	"
4135	.....	104	18.0	23.0	.. ..	.. ..	.. ..	.. ..	
4235	.....	114	19.9	23.0	3 15	6 05	3 57	7 05	"
4505	.....	130	18.2	21.7	4 40	8 10	5 30	9 15	"
4605	.....	130	18.1	22.8	2 55	6 05	4 00	7 35	"

STRENGTH TESTS.

1 : 3 Standard sand mortar.

Specimens stored in water; tested wet.

In general, values for strength are the average of five tests made on different days.

Cement Lot No.	Admixture, per cent by weight.	Used in Series.	Water, per cent by weight.	Tensile Strength (Briquettes), lb. per sq. in.					Compressive Strength (2 by 4-in. Cylinders), lb. per sq. in.				
				7 d.	28 d.	3 mo.	6 mo.	1 yr.	7 d.	28 d.	3 mo.	6 mo.	1 yr.
3641	.....	58 – 59	10.4	210	320	330	360	320	1130	1890	2710	3360	3100
3642	10 (sand)[1]	"	10.3	190	290	340	360	340	1190	1920	2660	2970	2300
3643	20 "	"	10.3	180	260	330	340	340	1030	1830	2630	2660	3110
3644	30 "	"	10.3	150	240	300	350	340	790	1420	2130	2380	2270
3645	40 "	"	10.4	130	200	240	290	330	690	990	1720	1850	2040
3646	50 "	"	10.3	70	150	230	250	280	490	890	1380	1470	1620
3647	10 (slag)[1]	"	10.3	210	300	380	420	380	970	2330	3280	3770	2880
3648	20 "	"	10.3	210	310	370	340	370	1010	2070	3050	3150	2980
3649	30 "	"	10.3	180	290	370	350	410	930	1980	2960	3390	3260
3650	40 "	"	10.3	160	260	340	370	380	770	1660	2830	3280	3580
3651	50 "	"	10.3	150	270	390	400	410	630	1520	2840	3030	3400
4035	.....	100	10.3	250	380	400	420	370	1700	2640	3750	4120	3810
4505	.....	130	10.1	195	330	370	350	....	1590	3150	4170	3780	....
4605	.....	130	10.3	280	390	410	410	....	1950	2880	4170	4600	....

[1] Admixture added to cement prior to final grinding.

MATERIALS.

The concrete materials used in these investigations were of commercial quality. In general the cements were mixtures of equal parts of 4 or 5 brands of Portland cement purchased in the Chicago market. In Series 58 and 59 sand and slag cements were prepared by grinding a Portland cement with 10 to 50 per cent of the admixture (by weight) in a laboratory tube mill. In proportioning, all cements were assumed to weigh 94 lb. per cu. ft. Mortar strengths and miscellaneous tests of the cements are given in Table I.

The aggregates consisted of sand and gravel from the Elgin, Ill., pit of the Chicago Gravel Company. This is a well-graded material with a preponderance of limestone particles.

In many of the tests the aggregates were separated into a number of sizes by the screens mentioned below and recombined in order to secure predetermined sieve analyses. The sieve analyses of one group of aggregates graded in such a way as to give a constant fineness modulus are given in Table XI.

Sieve analysis, unit weights and fineness moduli of the aggregates are given in Table II. The fineness modulus is used as a measure of the size and grading of the aggregate; it is the sum of the percentages in the sieve analysis, divided by 100, using the following sizes from the W. S. Tyler Company's standard screen scale: 100, 48, 28, 14, 8, 4, $\frac{3}{8}$ in., $\frac{3}{4}$ in., and $1\frac{1}{2}$ in.[1]

The principal admixture used in this investigation was high calcium hydrated lime. In Series 130 high magnesium lime and 17 other admixtures were used. The miscellaneous admixtures were, in general, of about the same fineness as commercial Portland cement. Many of them were ground in a laboratory tube mill.

The fineness, unit weight and normal consistency of the admixtures are given in Table III. In the case of hydrated lime, kieselguhr, mica and a few other admixtures, it was impossible to determine the fineness by the ordinary sieving methods, hence values are not reported. Normal consistency was determined by the Vicat needle by the method used for Portland cement.

The water used was from Lake Michigan.

[1] For further details concerning the fineness modulus of aggregate, see "Design of Concrete Mixtures," *Bulletin 1*, Structural Materials Research Laboratory, Lewis Institute, Chicago.

TABLE II.—MISCELLANEOUS TESTS OF AGGREGATE.

Aggregate: sand and pebbles from Elgin, Ill.

Sieves were made of square mesh wire cloth manufactured by The W. S. Tyler Co. It will be noted that each sieve has a clear opening of twice the width of the preceding sieve.

See Table XI for sieve analyses of one group of aggregates in Series 114.

Series.	Size of Aggregate.	Weight, lb. per cu. ft.	Sieve Analysis, per cent coarser than each sieve.									Fineness Modulus.[b]
			100[a] (0.0058)	48 (0.0116)	28 (0.023)	14 (0.046)	8 (0.093)	4 (0.185)	3/8 (0.37)	3/4 (0.75)	1 1/2 (1.5)	
59	0 – No. 4	121	65	47	47	35	18	0	..	..	..	2.22
"	"	125	75	68	57	43	25	0	..	..	..	2.68
"	"	126	82	75	65	50	30	0	..	..	..	3.02
"	"	124	88	81	72	57	35	0	..	..	..	3.33
"	"	122	91	86	77	63	38	0	..	..	..	3.55
"	"	119	99	92	82	65	40	0	..	..	..	3.78
"	"	114	97	94	88	75	50	0	..	..	..	4.04
"	"	111	98	96	92	81	57	0	..	..	..	4.24
"	"	101	100	100	100	100	100	0	..	..	..	5.00
100	0 – No. 48	102	98	0	..	..	..	..	..	..	..	0.98
"	0 – No. 28	102	88	32	0	..	..	..	..	..	..	1.20
130	0 – No. 28	102	92	78	0	..	..	..	..	..	..	1.70
100, 114, 130	0 – No. 14	106	97	88	35	0	..	..	..	..	..	2.20
100, 114	0 – No. 8	108	98	92	50	20	0	..	..	..	..	2.60
100, 114, 130	0 – No. 4	112	99	93	63	40	20	0	..	..	..	3.15
100	0 – 3/8 in.	117	99	94	72	50	28	7	0	..	..	3.50
130	0 – 3/8 in.	120	99	94	71	60	46	30	0	..	..	4.00
114	0 – 3/8 in.	121	99	96	79	68	59	49	0	..	..	4.50
130	0 – 3/4 in.	126	100	96	80	73	63	53	35	0	..	5.00
114	0 – 3/4 in.	124	99	97	86	78	71	65	44	0	..	5.40
130	0 – 1 1/2 in.	125	99	93	68	55	39	23	17	6	0	4.00
130	"	130	99	95	79	70	59	49	37	12	0	5.00
130	"	130	100	95	84	77	70	62	46	16	0	5.50
58, 104, 114, 130	"	127	100	97	86	79	73	68	51	21	0	5.75
130	"	126	100	98	90	85	79	74	56	18	0	6.00
130	"	122	100	98	91	89	85	81	61	20	0	6.25
130	"	118	100	99	94	93	90	87	65	22	0	6.50
130	"	114	100	100	98	96	94	93	70	24	0	6.75

[a] Number of square openings per linear inch, or the size of opening in inches.

[b] Sum of percentages in sieve analysis, divided by 100.

TEST PIECES.

The size and number of test pieces in each series are indicated under Outline of Tests. All test pieces were made in metal forms. The concrete mixes are expressed as one part cement to a given number of volumes of aggregate mixed as used. For example a 1 : 5 mix indicates that 1 cu. ft. of cement is combined with 5 cu. ft. of mixed aggregate; this mixture is

TABLE III.—MISCELLANEOUS TESTS OF POWDERED ADMIXTURES.

Used in Series.	Kind.	Fineness Residue on each Sieve, per cent by weight.				Weight, lb. per cu. ft.	Specific Gravity.[1]	Normal Consistency, per cent by weight.
		200	100	48	28			
100	Hydrated lime	....	....	....	..	47	2.41	49.0
	Kaolin	....	....	....	..	56	2.51	50.0
	Kieselguhr	....	....	....	..	11	1.92	250.0
	Limestone	21.7	....	....	..	82	2.77	21.0
	Natural cement	24.0	....	....	..	68	2.82	36.0
	Slag	19.5	....	....	..	90	2.88	23.8
104	Hydrated lime	....	....	....	..	47	2.41	49.0
114	Hydrated lime	....	....	....	..	42	2.21	59.0
130	Brick	18.2	6.0	....	..	71	2.70	28.0
	Clay	....	....	....	..	34	2.53	45.0
	Fluorspar	57.0	37.9	13.0	0	135	3.10	15.0
	Gypsum	....	....	....	..	84	2.50	33.2
	Hydrated lime (high calcium)	....	....	....	..	40	2.21	60.0
	Hydrated lime (high magnesium)	....	....	....	..	40	2.48	60.0
	Ironite	91.0	45.0	18.0	0	186	6.90	8.4
	Kaolin	....	....	....	..	47	2.45	45.6
	Kieselguhr	....	....	....	..	13	2.00	230.0
	Lava	21.6	3.8	....	..	109	2.96	19.6
	Limestone	10.0	0.4	....	..	87	2.78	20.8
	Mica	....	....	....	..	48	2.81	....
	Natural cement	6.0	3.0	....	..	68	2.89	40.0
	Pitch	....	....	....	..	42	1.34	63.0
	Sand	20.3	0.2	....	..	90	2.64	22.0
	Slag	19.4	6.0	....	..	114	2.89	20.0
	Tufa	17.8	1.8	....	..	61	2.37	46.0
	Whiting	....	....	....	..	60	2.66	31.0
	Yellow ochre	....	....	....	..	83	3.27	42.0

[1] Values used in calculations for density of concrete. Determinations for the finely powdered admixtures were made with difficulty and they may vary a small amount from the true value.

about equivalent to the ordinary 1 : 2 : 4. The actual quantities of materials for a batch were determined by weight. The quantity of concrete required for one specimen was proportioned and mixed separately. Mixing was done by hand with a bricklayer's trowel in a galvanized iron pan.

The consistency of the concrete is an important feature. The quantity of water required by a unit volume of concrete will depend on the following factors:

1. The "workability" or the "relative consistency" of the concrete;
2. The quantity of cement (the mix);
3. The normal consistency of the cement;
4. The size and grading of the aggregate;
5. The absorption of the aggregate;
6. The water contained in the aggregate;
7. The normal consistency of the admixtures;
8. The quantity of admixture.

In proportioning the quantity of water for a batch of concrete in experimental work where we are endeavoring to establish fundamental principles, it is necessary to take all these factors into account. The quantity of the water to be used in a given batch was calculated by a formula which had been derived from earlier tests.

For the tests in Series 130, the plastic condition of the concrete was determined by the "slump test." This test was made by placing the specimens in a 6 by 12-in. steel cylinder form in the usual manner, by puddling in 3 layers with a $\frac{5}{8}$-in. steel bar pointed at the lower end. Immediately after molding, the form was slipped off by a steady upward pull. The shortening of the cylinder measured in inches is the "slump." A relative consistency of 1.00 or normal consistency is such as will give a slump of about $\frac{1}{2}$ to 1 in. Other "relative consistencies" require a proportional part of the quantity of water necessary for normal consistency. For example, a relative consistency of 1.10 requires 10 per cent more water than normal consistency.

In discussing the effect of water in concrete, the quantity of water is expressed in terms of the volume of cement; this is the water ratio.

The concrete was placed in the 6 by 12-in. cylinder molds in layers of about 4 in.; each layer was puddled by means of a $\frac{5}{8}$-in. round steel bar. The cylinders were capped when molded by means of neat cement paste and a piece of plate glass. The cylinders were removed from the forms on the day following molding, except for the 1 : 9 mix, which in some instances remained in the forms 2 days. In each series of investigations, one round of specimens was completed before the second round

was begun. In this way each value is the average of 5 or more entirely independent tests, made on different days.

Wear tests were made on concrete blocks, 8 by 8 by 5 in. These blocks were molded in the same manner as indicated for the cylinders. The top surface was finished with a wood float and covered with building paper and damp sand until the forms were removed.

The bond-test pieces were made by imbedding 24-in. lengths of 1-in. plain round bars axially in 8 by 8-in. concrete cylinders.

All specimens were stored in damp sand until time of test, unless otherwise noted.

METHODS OF TESTING.

Mortar strength and miscellaneous tests of cement were made in accordance with the standard methods of the American Society for Testing Materials.

Compression tests of mortar cylinders were made in a 40,000-lb. Riehle testing machine. The 6 by 12-in. concrete cylinders were tested in a 200,000-lb. Olsen machine. A spherical bearing block was used on top of the cylinders.

Wear tests were made in the Talbot-Jones rattler, using blocks 8 in. square and 5 in. thick. The blocks were placed as shown in Fig. 14. The outside diameter of the ten-sided polygon thus formed is 36 in. During the test the front of the chamber was closed by means of a steel plate. The abrasive charge consisted of 200 lb. of cast-iron balls (10 of $3\frac{3}{4}$-in. and about 140 of $1\frac{7}{8}$-in. diameter). These balls conform to the requirements for the standard rattler test of paving brick of the American Society for Testing Materials.

The test consisted of exposing the inner faces of the concrete blocks to the wearing action of the charge for 1800 revolutions at the rate of 30 r.p.m. The machine was run for 900 revolutions in one direction, then reversed. The loss in weight during the test reduced to an equivalent depth was used as a measure of the wear.

Tests of bond between concrete and steel consisted of pull-out tests of 1-in. plain round steel bars imbedded 8 in. in an 8-in. concrete cylinder. Slip-of-bar measurements were made

during the test. The method of conducting the tests was similar to that used by the writer at the University of Illinois.[1]

Evaporation and absorption tests were made by weighing the blocks used in the wear tests.

TEST DATA.

Practically all of the test data from the six investigations of powdered admixtures mentioned above are given in the

TABLE IV.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75; for sieve analyses see Table II.

Admixture added to materials in batch, expressed as percentage of *volume* of cement.

Specimens stored in damp sand until tested.

Each value is the average of five tests made on different days.

Data platted in Fig. 3; See also Table XVIII.

Hydrated Lime, per cent of Cement.		Water, ratio to volume of cement.						Compressive Strength, lb. per sq. in. (age, 28 days).					
By Volume.	By Weight.	0.90[1]	1.00	1.10[1]	1.25	1.50	2.00	0.90[1]	1.00	1.10[1]	1.25	1.50	2.00
MIX 1 : 9 BY VOLUME.													
0	0	1.11	1.21	1.32	1.47	...	...	1490	1290	1260[2]	960	...	...
5	2.1	1.13	1.23	1.34	1.50	...	...	1300	1320	1160	920	...	...
10	4.2	1.15	1.25	1.36	1.52	...	...	1440	1380	1190[2]	940	...	...
20	8.5	1.19	1.29	1.40	1.57	...	...	1480	1360	1260[2]	910	...	...
33	14.0	1.23	1.34	1.46	1.63	...	...	1370	1300	1070[2]	930	...	...
								Av. 1420	1330	1190	930		
MIX 1 : 6 BY VOLUME.													
0	0	0.84	0.92	1.00	1.12	...	...	2400	2250	2230[2]	1620	...	...
5	2.1	0.86	0.94	1.02	1.14	...	...	2350	2390	2120	1670	...	...
10	4.2	0.88	0.96	1.01	1.17	...	...	2510	2480	2170[2]	1620	...	...
20	8.5	0.91	1.00	1.09	1.22	...	...	2480	2420	2190[2]	1620	...	...
33	14.0	0.96	1.05	1.14	1.27	...	...	2430	2310	2070[2]	1430	...	...
								Av. 2430	2370	2160	1590		
MIX 1 : 5 BY VOLUME.													
0	0	0.74	0.82	0.89	1.00	1.18	1.54	2970	3040	2670	2040	1260	700
5	2.1	0.76	0.84	0.91	1.03	1.21	1.58	2740	2840	2570	2010	1210	670
10	4.2	0.78	0.86	0.94	1.04	1.24	1.63	2930	3010	2560	2010	1160	680
20	8.5	0.81	0.90	0.97	1.10	1.30	1.70	2910	2820	2430	1900	1020	590
33	14.0	0.86	0.94	1.03	1.16	1.37	1.80	2840	2810	2350	1730	930	490
50	21.3	0.92	1.01	1.10	1.24	1.48	1.93	2770	2600	2200	1600	950	470
								Av. 2860	2850	2460	1880	1090	600

[1] Relative consistency of concrete.
[2] Average of 10 or 15 tests.

[1] See "Tests of Bond between Concrete and Steel," *Bulletin 71*, University of Illinois Eng. Exp. Station.

TABLE IV.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.—*Continued.*

Hydrated Lime, per cent of Cement.		Water, ratio to volume of cement.						Compressive Strength, lb. per sq. in. (age, 28 days).					
By Volume.	By Weight.	0.90[1]	1.01	1.10[1]	1.25	1.50	2.00	0.90[1]	1.00	1.10[1]	1.25	1.50	2.00
						MIX 1 : 4 BY VOLUME.							
0	0	0.65	0.72	0.78	0.88	1.04	1.36	3580[2]	3710[2]	3540[2]	2600[2]	1550[2]	800[2]
5	2.1	0.66	0.74	0.80	0.90	1.08	1.40	3940	3600	3320	2570	1320	870
10	4.2	0.69	0.76	0.83	0.93	1.10	1.44	3690	3580	3200	2400	1440	790
20	8.5	0.72	0.80	0.87	0.98	1.16	1.52	3870	3370	2890	2340	1410	790
33	14.0	0.76	0.85	0.92	1.04	1.24	1.62	3390	3000	2600	2040	1340	620
50	21.3	0.82	0.91	1.00	1.12	1.33	1.74	3090	2700	2430	1910	1140	520
								Av. 3590	3320	3000	2300	1370	740
						MIX 1 : 3 BY VOLUME.							
0	0	0.56	0.62	0.68	0.76	0.90	1.19	4520	4450	4200	3330	2000	1110
5	2.1	0.58	0.64	0.70	0.78	0.93	1.23	4240	4170	3780	3400	2150	1040
10	4.2	0.60	0.66	0.72	0.81	0.96	1.27	3880	4050	3780	3350	2030	1000
20	8.5	0.63	0.70	0.76	0.85	1.02	1.35	3680	4000	3300	3130	1940	760
33	14.0	0.67	0.75	0.82	0.91	1.09	1.45	3750	3460	3080	2520	1560	880
50	21.3	0.73	0.82	0.89	0.99	1.19	1.57	3160	3140	2590	2250	1440	720
								Av. 3870	3880	3460	3000	1850	920
						MIX 1 : 2 BY VOLUME.							
0	0	0.47	0.52	0.57	0.64	0.77	1.01	5080	4860	4830	3770	2970	1450
5	2.1	0.49	0.54	0.59	0.67	0.80	1.05	5240	4610	4530	3830	2750	1360
10	4.2	0.50	0.56	0.62	0.69	0.83	1.09	5060	4820	4310	3780	2660	1180
20	8.5	0.54	0.60	0.66	0.74	0.88	1.17	4780	4130	3870	3440	2850	1180
33	14.0	0.58	0.65	0.71	0.80	0.96	1.27	3920	4090	3630	3120	2210	1060
50	21.3	0.64	0.71	0.78	0.88	1.06	1.40	3420	3410	3160	2860	2150	890
								Av. 4580	4320	4060	3470	2600	1190

[1] Relative consistency of concrete.
[2] Average of 10 or 15 tests.

attached tables and diagrams. Most consideration has been given to the results of tests in Series 114 and 130; in making these tests we had the benefit of the data and experience gained in earlier work. The principal results of tests in each of Series 58, 59 and 100, are presented by a single diagram; see Figs. 10, 11 and 12. The tests in Series 104 are given in Table X.

The values given in the tables and diagrams are in general the average of five or more tests. In the discussion all values are given equal weight whether based on 5, 10 or 15 tests. In many instances the results of tests of concrete containing powdered admixtures have been reduced to (*a*) percentages of the strength of similar concrete without admixtures;

TABLE V.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders.
Mix by volume. Relative consistency of concrete, 1.10.
Aggregate: sand and pebbles from Elgin, Ill.; graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch, expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests, unless otherwise noted.
See relative consistency 1.10 in Table IV for water-ratio of concrete.
The 1-year tests in this series are not due.
Data platted in Fig. 4 and Table XIX.

Hydrated Lime, per cent of Cement.		Compressive Strength, for Different Mixes, lb. per sq. in.					
By Volume.	By Weight.	1 : 9	1 : 6	1 : 5	1 : 4	1 : 3	1 : 2
AGE AT TEST, 3 DAYS.							
0	0	280	550	770	1030[2]	1280	1790
5	2.1	330	560	790	990	1150	1650
10	4.2	320	610	780	960	1210	1600
20	8.5	300	580	780	830	1130	1470
33	14.0	320	560	680	740	1010	1250
50	21.3	300	480	660	890	1140	1130
		Average 310	560	740	910	1150	1480
AGE AT TEST, 7 DAYS.							
0	0	640	1030	1250	1860[2]	2550	2690
5	2.1	630	1120	1400	1720	2280	2900
10	4.2	620	1170	1420	1880	2170	2610
20	8.5	650	1140	1370	1690	2090	2300
33	14.0	590	1160	1220	1590	1890	2180
50	21.3	610	990	1150	1440	1710	1790
		Average 620	1100	1300	1700	2120	2410
AGE AT TEST, 28 DAYS.[1]							
0	0	1260[2]	2230[2]	2670	3540[2]	4200	4830
5	2.1	1160	2120	2570	3320	3780	4530
10	4.2	1190[2]	2170[2]	2560	3200	3780	4310
20	8.5	1260[2]	2190[2]	2430	2890	3300	3870
33	14.0	1070[2]	2070[2]	2350	2600	3080	3630
50	21.3	1190	1940	2200	2430	2590	3160
		Average 1190	2120	2460	3000	3460	4060
AGE AT TEST, 3 MONTHS.							
0	0	1650	2990	3500	4370[2]	4970	4980
5	2.1	1750	3070	3740	4050	4630	4720
10	4.2	1750	2960	3320	4270	4900	5070
20	8.5	1780	2880	3240	3760	4510	4280
33	14.0	1720	2820	3110	3540	4270	4230
50	21.3	1700	2420	2790	3260	3630	3640
		Average 1720	2860	3280	3880	4480	4490

[1] Same as values for relative consistency 1.10 in Table III.
[2] Average of 10 or 15 tests.

(*b*) per cent change in strength due to the presence of admixtures. These methods are helpful in showing the effect at a glance.

DISCUSSION OF TESTS.

Due to the large number of tests covered by this report the discussion will necessarily be confined to the most important topics. For many other features the reader must refer to the accompanying tables and diagrams. An excellent check on the uniformity of the tests is found in the concordance of the data as shown by the regularity of the points on the curves, and from the fact that tests made in different series at intervals of several months give essentially the same results. The word *concrete* is here used in its general sense to include what are usually referred to as *mortar* mixes.

The general effect of admixtures is to reduce the strength of concrete in proportion to the quantity of admixture used. Some exceptions to this general conclusion are mentioned below.

EFFECT OF HYDRATED LIME AS AN ADMIXTURE IN CONCRETE.

The principal tests with hydrated lime are given in Tables IV to XII; the change in strength is shown in Tables XVII to XIX. It is impracticable in all cases to discuss separately the effects due to different causes, owing to the fact that in many instances two or more factors, such as mix, consistency, size of aggregate, age, etc., were varied simultaneously. Unless otherwise noted, the quantity of hydrated lime is expressed in terms of the volume of cement and was *added* to the cement. If it is desired to deal with weights, the necessary data will be found in Table III.

Concrete of Different Consistencies.—The effect of hydrated lime, using concrete of different consistencies is shown in Table IV. The consistencies ranged from relative consistency 0.90 (dry) to 2.00 (very wet), the mix from 1 : 9 to 1 : 2. Tests were made at 28 days in Series 130. Similar tests for 1 : 4 mix only were made in Series 114, at ages of 7 days to 1 year. See Fig. 1.

The strength of the concrete, both with and without hydrated lime, was reduced by the addition of water. The maximum strength was found for relative consistency of 0.90. The strength of the concrete was reduced by hydrated lime for all

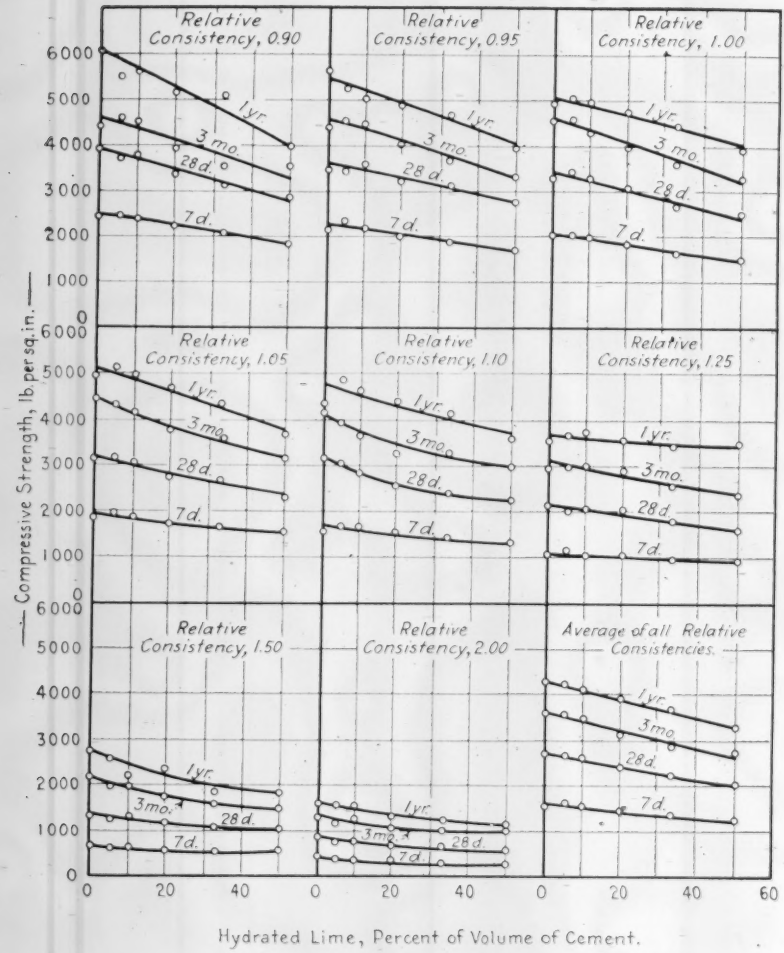


FIG. 1.—Effect of Hydrated Lime on the Strength of Concrete.

(Different Consistencies and Ages—Series 114.)

Compression tests of 6-by 12-in. concrete cylinders.
Mix, 1 : 4 by volume.
Sand and pebble aggregate, graded 0–1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Figs. 2 to 5.

consistencies and ages. The percentage reduction in strength for different consistencies is shown in Tables XVIII and XIX. These values were calculated from the slopes of the

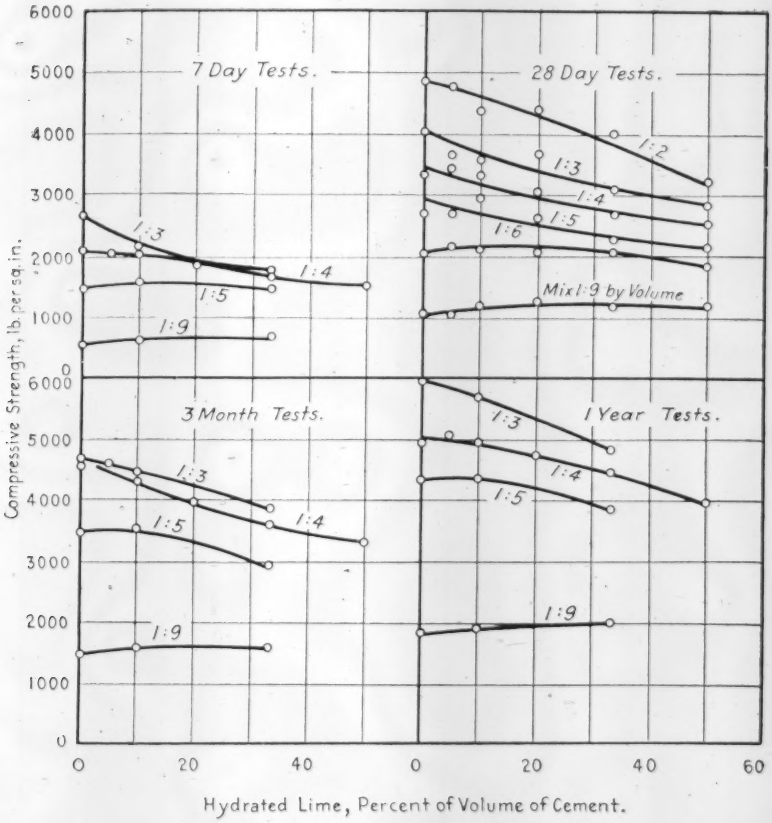


FIG. 2.—Effect of Hydrated Lime on the Strength of Concrete.

(Different Mixes and Ages—Series 114.)

Compression tests of 6 by 12-in. concrete cylinders.
Relative consistency of concrete, 1.00.
Sand and pebble aggregate, graded 0–1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Figs. 1, 3, 4 and 5.

curves in Figs. 1 and 3. It will be noted that in these figures the relation between the strength and volume of hydrated lime used is essentially a linear one. The wetter consistencies are

TABLE VI.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

(Series 130.)

Compression tests of 6 by 12-in. cylinders.
Mix by volume. Relative consistency of concrete, 1.10.
Hydrated Lime added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Data platted in Fig. 5 and Table XVIII.

Fineness Modulus of Aggregate.	Hydrated Lime, per cent of cement.		Water, ratio to volume of cement.					Compressive Strength, lb. per sq. in. (age, 28 days)					
	By Volume.	By Weight.	1 : 9	1 : 6	1 : 5	1 : 4	1 : 3	1 : 9	1 : 6	1 : 5	1 : 4	1 : 3	Average.
4.00[1]	0	0	1.70	1.26	1.11	0.96	0.81	440	1120	1270	1630	3140	1520
"	10	4.2	1.75	1.30	1.15	1.00	0.85	480	920	1350	2000	3120	1570
"	20	8.5	1.79	1.35	1.20	1.04	0.90	510	960	1420	2010	2940	1570
"	33	14.0	1.85	1.40	1.25	1.10	0.95	500	1000	1420	2130	2860	1580
"	50	21.3	1.90	1.47	1.33	1.17	1.02	550	1060	1370	1860	2380	1440
								Av. 500	1010	1370	1930	2890	1540
5.00[1]	0	0	1.47	1.10	0.97	0.85	0.73	800	1620	2210	2910	3910	2290
"	10	4.2	1.52	1.14	1.01	0.90	0.77	780	1630	2330	3020	3630	2280
"	20	8.5	1.56	1.19	1.06	0.94	0.81	850	1760	2320	2820	3670	2280
"	33	14.0	1.62	1.24	1.11	0.99	0.87	840	1700	2120	2570	3080	2060
"	50	21.3	1.67	1.31	1.19	1.07	0.94	900	1500	2040	2400	2560	1880
								Av. 830	1640	2200	2740	3370	2140
5.50[1]	0	0	1.36	1.03	0.92	0.80	0.69	1100	2040	2790	3370	4280	2720
"	10	4.2	1.40	1.07	0.96	0.85	0.73	1090	2050	2660	3320	3980	2620
"	20	8.5	1.44	1.12	1.00	0.89	0.77	1100	2060	2620	3090	3560	2490
"	33	14.0	1.50	1.17	1.06	0.94	0.83	1080	2060	2330	2890	3120	2300
"	50	21.3	1.56	1.24	1.13	1.02	0.90	1080	1980	2070	2540	3050	2140
								Av. 1090	2040	2490	3040	3600	2450
5.75[1]	0	0	1.32	1.00	0.89	0.78	0.68	1260[2]	2230[2]	2670	3540[2]	4200	2780
"	10	4.2	1.36	1.04	0.94	0.83	0.72	1190[2]	2170[2]	2560	3200	3780	2580
"	20	8.5	1.40	1.09	0.97	0.87	0.76	1260[2]	2190[2]	2430	2890	3300	2410
"	33	14.0	1.46	1.14	1.03	0.92	0.82	1070[2]	2070[2]	2350	2600	3080	2230
"	50	21.3	1.52	1.21	1.10	1.00	0.89	1190[2]	1190[2]	2200	2430	2590	1920
								Av. 1190	1970	2440	2930	3390	2380
6.00[1]	0	0	1.27	0.96	0.86	0.76	0.66	1260	2100	2710	3390	4430	2780
"	10	4.2	1.31	1.00	0.90	0.80	0.70	1240	2150	2530	3370	3850	2630
"	20	8.5	1.36	1.05	0.95	0.84	0.74	1210	2100	2450	3150	3530	2490
"	33	14.0	1.41	1.10	1.00	0.90	0.80	1140	1950	2450	2820	3350	2340
"	50	21.3	1.47	1.17	1.07	0.97	0.87	1100	1830	2270	2730	3090	2200
								Av. 1190	2030	2480	3090	3650	2490
6.25[1]	0	0	1.22	0.93	0.84	0.74	0.65	1140	1940	2500	3150	4080	2560
"	10	4.2	1.26	0.98	0.88	0.78	0.69	990	1840	2340	3130	3810	2420
"	20	8.5	1.31	1.02	0.92	0.82	0.73	970	1960	2280	3280	3520	2400
"	33	14.0	1.36	1.07	0.98	0.88	0.79	980	1810	2190	2980	3470	2230
"	50	21.3	1.44	1.14	1.05	0.95	0.86	950	1730	2020	2680	2810	2040
								Av. 1010	1860	2270	3040	3480	2330
6.50[1]	0	0	1.18	0.90	0.81	0.72	0.63	740	1610	2000	2790	3490	2130
"	10	4.2	1.23	0.94	0.85	0.76	0.67	860	1550	2200	2780	3600	2200
"	20	8.5	1.27	0.98	0.90	0.80	0.71	700	1480	1990	3110	3250	2110
"	33	14.0	1.33	1.04	0.95	0.86	0.77	870	1760	2170	2810	3340	2190
"	50	21.3	1.39	1.11	1.03	0.93	0.84	770	1580	2090	2690	2800	1990
								Av. 790	1600	2090	2840	3300	2120
6.75[1]	0	0	....	....	....	0.70	0.62	....	....	....	2540	3470	....
"	10	4.2	....	....	....	0.74	0.66	....	....	....	2430	3340	....
"	20	8.5	....	....	....	0.78	0.70	....	....	....	2390	3100	....
"	33	14.0	....	....	....	0.84	0.76	....	....	....	2460	3040	....
"	50	21.3	....	....	....	0.91	0.83	....	....	....	2470	2630	....
								Av.	....	....	2460	3120	....

[1] All aggregate sand and pebbles from Elgin, Ill., graded 0–1½ in. Different values of fineness modulus were obtained by varying the proportions of sand and pebbles. For sieve analysis see Table II.
[2] Average of 10 or 15 tests.

more affected by the presence of hydrated lime than the drier ones. In Series 130, in the case of the 1 : 4 mix, representing concrete of the quality used in road construction, the reduction in

TABLE VII.—EFFECT OF HYDRATED LIME ON THE STRENGTH OF CONCRETE.

Compression tests of 6 by 12-in. cylinders.
Aggregate: sand and pebbles from Elgin, Ill.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
See Table II for sieve analysis of aggregates.

Hydrated Lime, per cent of cement.		For Different Sizes of Aggregates.														
		Water, ratio to volume of cement.							Compressive Strength, lb. per sq. in. (age, 28 days)							
By Volume.	By Weight.	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to 3/8 in.	0 to 3/4 in.	0 to 1 1/2 in.	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to 3/8 in.	0 to 3/4 in.	0 to 1 1/2 in.
1 : 5 MIX. RELATIVE CONSISTENCY, 1.10. SERIES 130.																
0	0	1.52	1.42	....	1.26	1.10	0.97	0.89	470	540	....	1010	1490	2140	2670
5	2.1	1.54	1.44	....	1.28	1.12	0.99	0.91	440	550	....	990	1600	2340	2570
10	4.2	1.56	1.47	....	1.31	1.15	1.01	0.94	450	570	....	980	1620	2440	2560
20	8.5	1.60	1.51	....	1.35	1.19	1.05	0.97	500	630	....	1050	1630	2260	2430
33	14.0	1.65	1.57	....	1.40	1.24	1.11	1.04	460	600	....	1070	1530	1870	2350
50	21.3	1.73	1.64	....	1.47	1.32	1.18	1.10	530	660	....	1050	1560	1740	2200
									Av. 480	590		1020	1570	2130	2460
1 : 4 MIX. RELATIVE CONSISTENCY, 1.10. SERIES 130.																
0	0	1.29	1.21	....	1.09	0.95	0.85	0.78	760	840	....	1360	2130	2820	3540[1]
5	2.1	1.31	1.23	....	1.11	0.97	0.87	0.80	690	830	....	1490	2300	2900	3320
10	4.2	1.33	1.26	....	1.15	0.99	0.89	0.83	750	950	....	1480	2250	2680	3200
20	8.5	1.38	1.30	....	1.18	1.04	0.94	0.87	760	880	....	1540	2260	2720	2890
33	14.0	1.43	1.35	....	1.23	1.09	0.99	0.92	740	940	....	1520	2230	2460	2600
50	21.3	1.50	1.43	....	1.30	1.16	1.06	1.00	850	980	....	1330	1900	2420	2430
									Av. 760	900		1450	2180	2670	3000
1 : 4 MIX. RELATIVE CONSISTENCY, 1.00. SERIES 114.																
0	0	....	1.13	1.07	1.00	0.83	0.77	0.73	....	970	1170	1360	2490	3530	3310
5	2.2	....	1.15	1.09	1.02	0.85	0.79	0.75	....	990	1140	1420	2640	3250	3470
10	4.5	....	1.17	1.11	1.04	0.87	0.81	0.77	....	950	1180	1440	2580	3290	3300
20	8.9	....	1.21	1.15	1.08	0.91	0.85	0.81	....	950	1160	1520	2600	2910	3090
33	14.7	....	1.26	1.20	1.13	0.96	0.90	0.86	....	1020	1200	1560	2480	2630	2670
50	22.3	....	1.33	1.27	1.20	1.03	0.97	0.93	....	1060	1290	1610	2330	2390	2500
									Av.	990	1190	1480	2520	3000	3060

[1] Average of 15 tests.

strength at 28 days for relative consistency 1.00, is 0.48 per cent for each 1 per cent of hydrated lime; for relative consistency 2.00, this value is increased to 0.62 per cent. In Series 114 the corresponding values are 0.66 and 0.74.

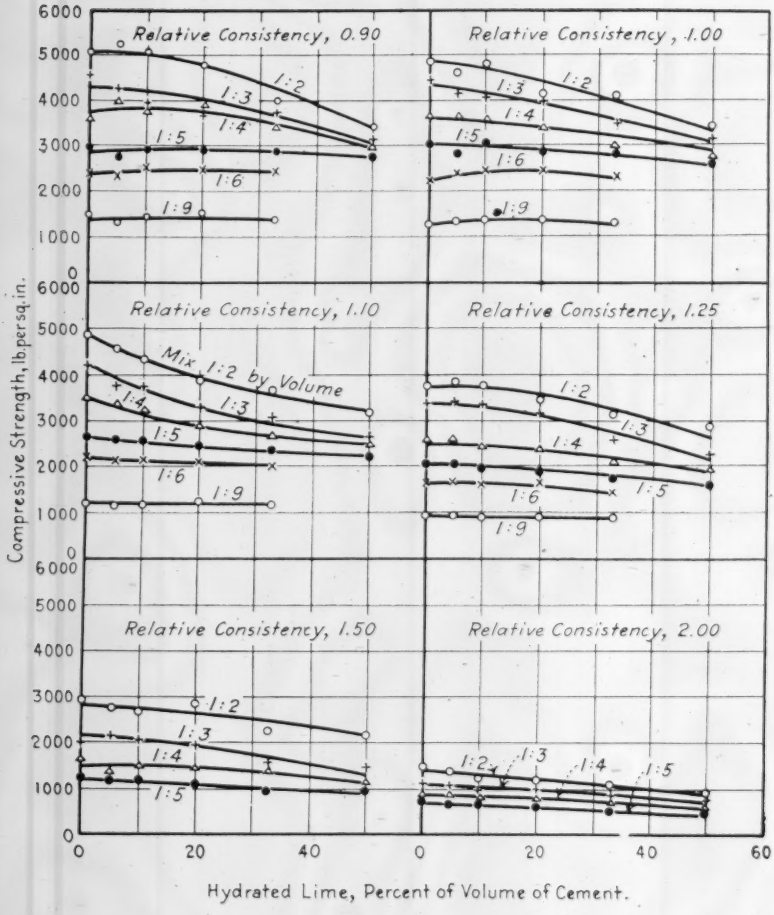


FIG. 3.—Effect of Hydrated Lime on the Strength of Concrete.

(Different Mixes and Consistencies—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table IV.
Sand and pebble aggregate, graded 0–1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp at age of 28 days.
Each value is the average of five tests made on different days.
Compare Figs. 1, 2, 4 and 5.

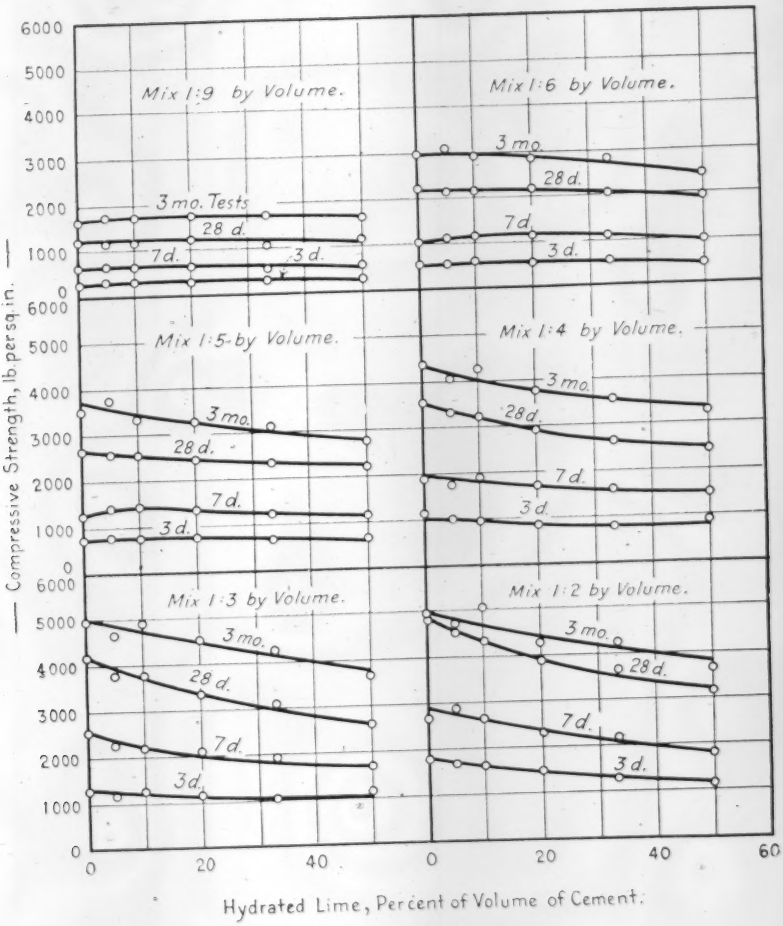


FIG. 4.—Effect of Hydrated Lime on the Strength of Concrete.

(Different Mixes and Ages—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table V.
Mix by volume.
Sand and pebble aggregate, graded 0–1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Compare Figs. 1 to 3 and 5.

Water Constant.—Table XII gives the results of a series of tests in which hydrated lime up to 50 per cent of the volume of the cement was used in mixes of 1 : 5, 1 : 4 and 1 : 3 proportion. The concrete was mixed with a quantity of water which gave a normal consistency with 50 per cent of hydrated lime; other batches were mixed with the same quantity of water. This gave a graduated series of consistencies, the mix without hydrated lime being considerably wetter than the others. These tests

TABLE VIII.—EFFECT OF NATURAL CEMENT ON THE STRENGTH OF PORTLAND CEMENT CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders.

Mix 1 volume of *Portland* cement to 4 volumes of mixed aggregate.

Aggregate: sand and pebbles from Elgin, Ill.; graded 0-1½ in.; fineness modulus 5.75; for sieve analyses see Table II.

Natural cement added to materials in batch; expressed as percentage of *volume* of Portland cement.

Specimens stored in damp sand; tested damp.

Each value is the average of five tests made on different days.

Natural Cement, per cent of Portland Cement.		Compressive Strength, lb. per sq. in.									
		For Different Ages. Relative Consistency, 1.10.				For Different Relative Consistencies. Age at Test, 28 days.					
By Volume.	By Weight.	3 d.	7 d.	28 d.	3 mo.	0.90	1.00	1.10	1.25	1.50	2.00
0	0	1030[1]	1860[1]	3540[1]	4370[1]	3580[1]	3710[1]	3540[1]	2600[1]	1550[1]	800[1]
10	7.2	1080	1850	2970	4130	3450	3320	2970	2190	1530	740
20	14.5	1080	1720	2910	4110	3380	3680	2910	2200	1480	700
33	23.9	1050	1620	2820	3950	3560	3400	2820	2180	1380	650
50	36.2	960	1610	2800	3640	3250	2990	2800	1980	1120	660
75	54.3	920	1510	2400	3380	2930	2930	2400	1970	1240	570
Natural cement	only[2].....	810	1360	2320	3170	2760	2440	2320	1650	1270	520

[1] Average of 10 or 15 tests.

[2] This mixture is on the same basis as the Portland cement mixture containing *no* natural cement, that is, the proportions are one volume of cement and four volumes of mixed aggregate. It should be noted that the other mixtures in this table are on a somewhat different basis, in that the quantity of Portland cement is constant.

show that with the water constant, the strength of concrete is practically uniform.

Water-Ratio–Strength Relation.—The water-ratio is defined as the ratio of the volume of water to volume of cement in the batch, considering 94 lb. of cement as 1 cu. ft. Many previous investigations have shown that there is a fixed relation between the water ratio and the strength of concrete, regardless of the reason for the use of a particular quantity of water, so long as the concrete is plastic and the aggregate is not too coarse for the quantity of cement used. The water ratio - strength relation

TABLE IX.—EFFECT OF STORAGE CONDITION ON THE STRENGTH OF CONCRETE CONTAINING HYDRATED LIME.

(Data from Series 114.)

Compression tests of 6 by 12-in. concrete cylinders.
1 : 4 mix by volume; hand-mixed concrete; relative consistency, 1.00.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Hydrated lime was added as a percentage of the volume of the cement.
Each value is the average of five tests made on different days.
Data platted in Fig. 9.
Tests at two and five years not due.

Age at Test.	Compressive Strength of Concrete Stored in Damp Sand for Times Indicated, Remainder in Air.																			
	Strength, lb. per sq. in.										Strength, per cent.									
	Damp Sand.[1]	1[2] d.	2 d.	4 d.	7 d.	14 d.	28 d.	3 mo.	6 mo.	1 yr.	1[2] d.	2 d.	4 d.	7 d.	14 d.	28 d.	3 mo.	6 mo.	1 yr.
HYDRATED LIME, 0 per cent.																				
7 days	2090	1890	2010	1930	2090						90	96	92	100					
14 days	2750	2410	2690	2750	2770	2750					88	98	100	100	100				
21 days	3100					3230									104				
28 days	3400	2980	3020	3070	3670	3780	3400				88	89	91	108	111	100			
2 mo.	4100						4200									102			
3 mo.	4300	2910	3390	3560	3950	4590	4600	4300			68	79	83	92	107	107	100		
3.5 mo.	4500							4730									105		
6 mo.	4800						4350	5320	4800							91	111	100	
7 mo.	4900								5500									112	
9 mo.	5000							4810	5680								97	113	
12 mo.	5150	2740	3010	3290	3750	4040	4350	5340	5770	5150	53	58	64	73	78	84	104	112	100
13 mo.	5170									5920									115
15 mo.	5200									6400									123
18 mo.	5220									6570									126
HYDRATED LIME, 10 per cent.																				
7 days	2010	1850	1830	2120	2010						92	91	106	100					
14 days	2700	2260	2500	2920	2940	2700					84	93	108	108	100				
21 days	3050					3270									108				
28 days	3300	2770	2930	3380	3300	3770	3300				84	89	102	100	114	100			
2 mo.	3900						4340									111			
3 mo.	4250	3120	3220	3620	4130	4550	4390	4250			73	76	85	97	107	104	100		
3.5 mo.	4350							4430									102		
6 mo.	4700						4060	4660	4700							86	99	100	
7 mo.	4800								5700									119	
9 mo.	4880							4610	5340								95	109	
12 mo.	4950	3190	3010	3440	3950	3850	4510	5230	5910	4950	64	61	69	80	78	91	106	120	100
13 mo.	5000									5650									113
15 mo.	5020									6160									123
18 mo.	5050									6320									126
HYDRATED LIME, 33 per cent.																				
7 days	1680	1570	1680	1740	1680						93	100	104	100					
14 days	2200	2080	2140	2320	2410	2200					95	97	106	110	100				
21 days	2450					2680									110				
28 days	2650	2330	2450	2750	3040	2940	2650				88	92	104	115	111	100			
2 mo.	3200						3680									115			
3 mo.	3500	2680	2660	3230	3790	3880	3990	3500			76	76	92	108	111	114	100		
3.5 mo.	3600							3890									108		
6 mo.	4000						3810	4460	4000							95	112	100	
7 mo.	4100								4460									109	
9 mo.	4300							4520	4940								105	115	
12 mo.	4500	2440	2560	3300	3420	3660	4060	4590	5400	4500	54	57	73	76	82	90	102	120	100
13 mo.	4600									4960									108
15 mo.	4700									5230									112
18 mo.	4800									5410									113

[1] Specimens stored in damp sand until test. Values interpolated from age-strength curves.
[2] Period stored in damp sand; stored in air remainder of time before test.

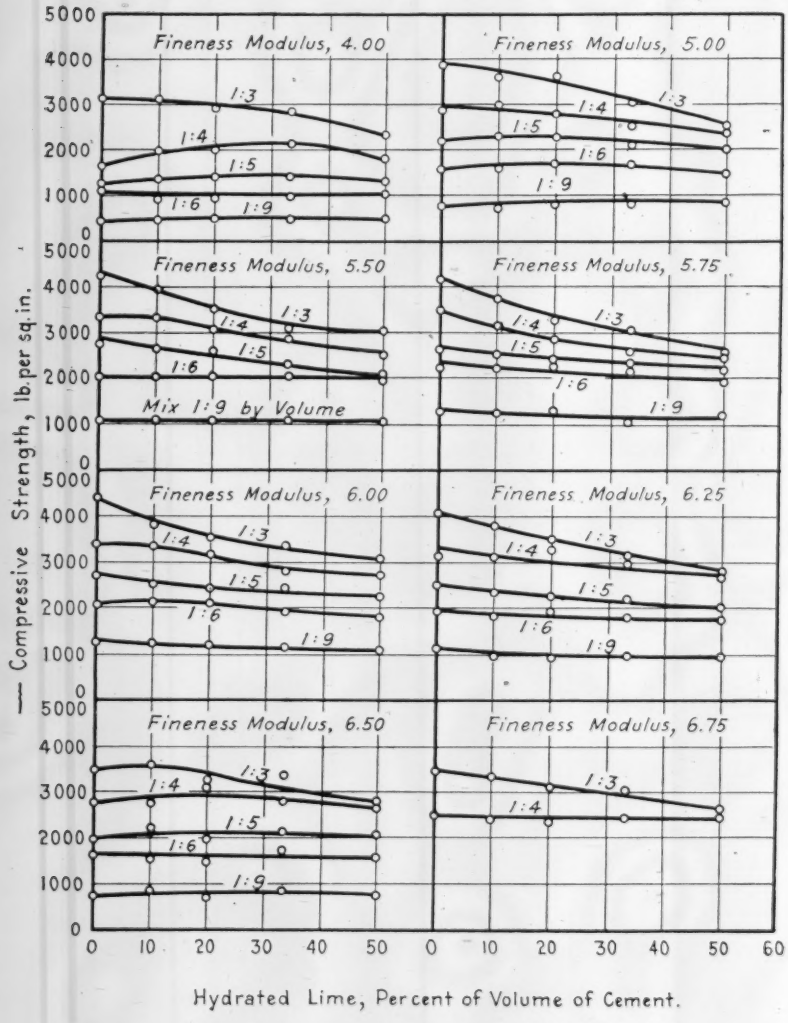


FIG. 5.—Effect of Hydrated Lime on the Strength of Concrete.

(Different Gradings of Aggregates and Mixes—Series 130.)

Compression tests of 6 by 12-in. concrete cylinders. Data from Table VI.
Specimens stored in damp sand; tested damp at age of 28 days.
Sand and pebble aggregate, graded 0–1½ in. Different values of fineness modulus were derived by combining sand and pebbles in different proportions. Values for fineness modulus 5.50 to 6.00, represent the usual range for aggregates of this size. For sieve analysis see Table II.

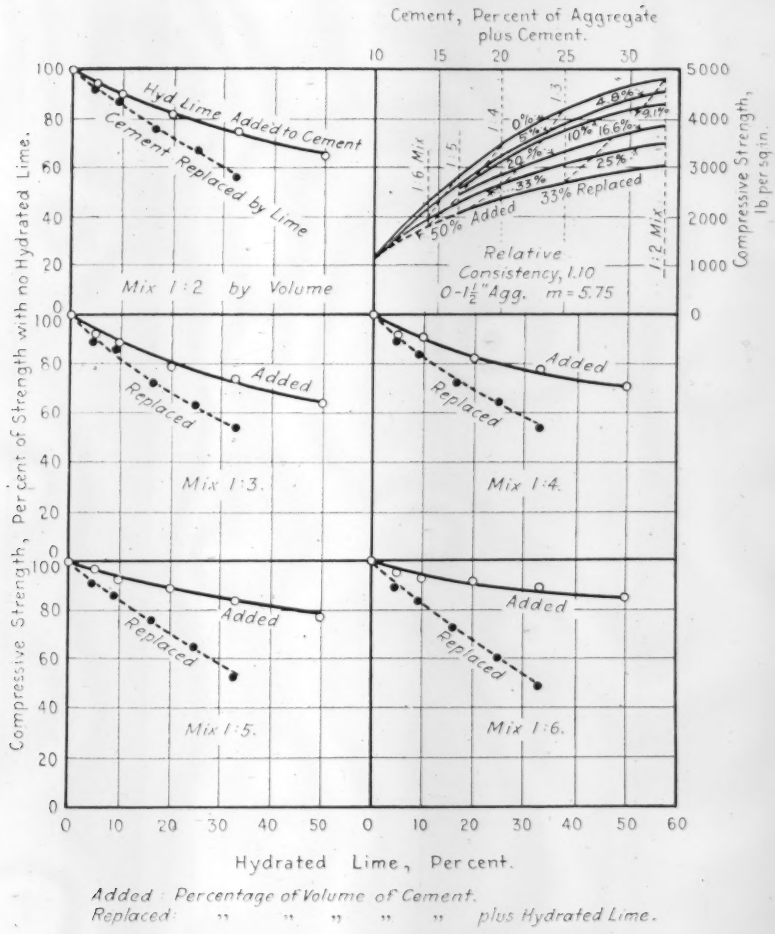


FIG. 6.—Effect of Hydrated Lime on the Strength of Concrete.

Compression tests of 6 by 12-in. cylinders; at age of 28 days.
Aggregate, sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Specimens stored in damp sand; tested damp.

In the upper right corner the relation between the strength of concrete and the quantity of cement is platted for different percentages of hydrated lime. In the tests hydrated lime was added to the cement; however, the effect of replacing cement by hydrated lime is also indicated. The intersections of the vertical dotted curves with the solid curves give the strengths of concrete when hydrated lime was added and the diagonal dotted lines give the strengths of concrete when the cement was replaced by hydrated lime.

The other diagrams in this figure show the relative strength of concrete of different mixtures, both where hydrated lime was added to the cement in the batch, and where the hydrated lime replaced cement.

Based on tests in Table IV.
Compare Figs. 11 and 12.

is platted in Fig. 7 for certain 28-day tests without hydrated lime and with 50 per cent hydrated lime. Similar curves may be drawn for other percentages. In computing the water-ratio, all water except that absorbed by the aggregate, was accredited to the cement; that is, the water absorbed by the hydrated lime was not deducted. These curves show that the water ratio - strength relation holds with and without hydrated lime, although the relation is not the same. It was found impracticable to determine the absorption of hydrated lime, although it is prob-

TABLE X.—EFFECT OF HYDRATED LIME ON THE COMPRESSIVE AND BOND STRENGTH OF CONCRETE.

(Data from Series 104.)

Compression tests of 6 by 12-in cylinders.
Full-out tests on 1-in. plain round bar embedded in 8 by 8-in. cylinders.
Mix, 1 : 5 by volume; relative consistency, 1.00.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
In this group of tests the hydrated lime *replaced* an equal volume of cement; therefore the *quantity* of *cement* decreased with increased percentage of hydrated lime. In all later tests hydrated lime was *added* to a fixed quantity of cement.

Hydrated Lime, per cent of cement plus hydrated lime.		Water-Ratio.[1]	Compressive Strength, lb. per sq. in.				Maximum Bond Stress, lb. per sq. in.			
By Volume.	By Weight.		7 d.	28 d.	3 mo.	1 yr.	7 d.	28 d.	3 mo.	1 yr.
0	0	0.88	1310	2730[2]	3550	4020	310	680[2]	760	910
5	2.6	0.91	1310	2410	3730	4120	300	660	740	940
10	5.3	0.96	1230	2660	3530	4000	380	530	710	910
20	11.1	1.08	1120	2280	2950	3800	370	410	720	860
33	19.8	1.30	810	1720	2260	3080	170	370	450	620
50	33.4	1.72	520	1030	1470	1510	160	240	460	400

[1] Ratio of volume of mixing water to volume of cement.
[2] Average of 15 tests made on 15 different days.

able that if correction could be made for this factor, the water ratio - strength relation would be found to hold for concrete containing admixtures in the same manner as has been found for those without admixtures. The water ratio of 1 : 4 mix, relative consistency 1.10, with aggregates of fineness modulus 5.75, without hydrated lime is 0.78; with 50 per cent hydrated lime it is 1.00. The strength in the first instance is 3100 lb. per sq. in., while with the 50 per cent hydrated lime it is 2400 lb. per sq. in. These curves bring out the water ratio - strength relation for given conditions but do not show directly the effect of hydrated lime on the strength of concrete.

The water ratio - strength relation for tests in Series 100 is shown in Fig. 10.

Mix.—The effect of hydrated lime on the strength of concretes of different mixes is shown in Tables IV to VII, XII and

TABLE XI.—EFFECT OF HYDRATED LIME ON THE STRENGTH AND WEAR OF CONCRETE.

(Data from Series 114.)

Compression tests of 6 by 12-in. cylinders.

Mix 1 : 4 by volume. Relative consistency, 1.10.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.

Hydrated lime added to materials in batch; expressed as per cent by *volume* of cement.

Specimens stored in damp sand; tested damp.

Each value for compression is the average of 5 tests made on different days; for wear average of 15 tests made on 3 different days.

Reference No.[1]	Sieve Analysis of Aggregate, Amount Coarser than Each Sieve, per cent by weight.									Aggregate.		For Different Percentages of Hydrated Lime.					
										Fineness Modulus.[2]	Surface Area.[3]	Compressive Strength, lb. per sq. in. (age, 28 days)			Depth of Wear, in. (age, 3 months)		
	No. 100	No. 48	No. 28	No. 14	No. 8	No. 4	⅜ in.	¾ in.	1½ in.			0 (0.78)[4]	10 (0.83)[4]	33 (0.92)[4]	0 (0.78)[4]	10 (0.83)[4]	33 (0.92)[4]
264	95	89	82	75	67	67	67	62	0	6.04	1565	2780	2620	2310	0.50	0.44	0.50
268	98	95	90	83	83	83	50	22	0	6.04	834	2530	2540	2280	0.48	0.46	0.60
269	98	94	90	86	83	80	55	18	0	6.04	898	2590	2610	2220	0.56	0.46	0.53
270	96	90	80	80	80	80	60	38	0	6.04	1391	2570	2660	2100	0.51	0.54	0.50
274	90	85	81	78	75	73	66	56	0	6.04	1992	2580	2410	2320	0.48	0.46	0.53
275	100	93	82	73	73	73	63	47	0	6.04	1076	2880	2610	2290	0.49	0.45	0.52
276	100	100	100	92	81	60	45	26	0	6.04	390	2930	2640	2460	0.52	0.52	0.58
279	100	99	96	91	80	50	50	38	0	6.04	514	3040	2700	2280	0.47	0.44	0.55
281	99	98	91	86	80	76	38	38	0	6.04	701	3030	2700	2480	0.46	0.56	0.58
284	99	98	91	85	80	76	67	8	0	6.04	685	2690	2790	2440	0.52	0.51	0.62
												Av. 2760	2630	2320	0.50	0.48	0.55
Minimum value												2530	2410	2100	0.46	0.44	0.50
Maximum value												3040	2790	2480	0.56	0.56	0.62
Mean variation from average, per cent												6.2	2.7	3.7	4.6	7.9	6.4

[1] Same as the numbers in Table II, *Bulletin 1* of the Structural Materials Research Laboratory, Lewis Institute, Chicago.

[2] Fineness modulus of aggregate; sum of the percentages in the sieve analysis, divided by 100.

[3] Surface area of aggregate; square inches per pound of aggregate. See "Proportioning the Materials of Mortars and Concretes by Surface Areas of Aggregates," by L. N. Edwards, *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II (1918).

[4] Ratio of mixing water to volume of cement.

XIV, and Figs. 2 to 5. The change in strength of concrete of different mixes, due to hydrated lime, is shown in Tables XVIII and XIX. In general the strength of concrete was reduced by hydrated lime for all mixes. The leaner mixes are, however, reduced only to a slight extent and the 1 : 9 mix (about the same as the usual 1 : $3\frac{1}{2}$: 7 mix) gave a slight increase in strength with hydrated lime. This slight increase in strength

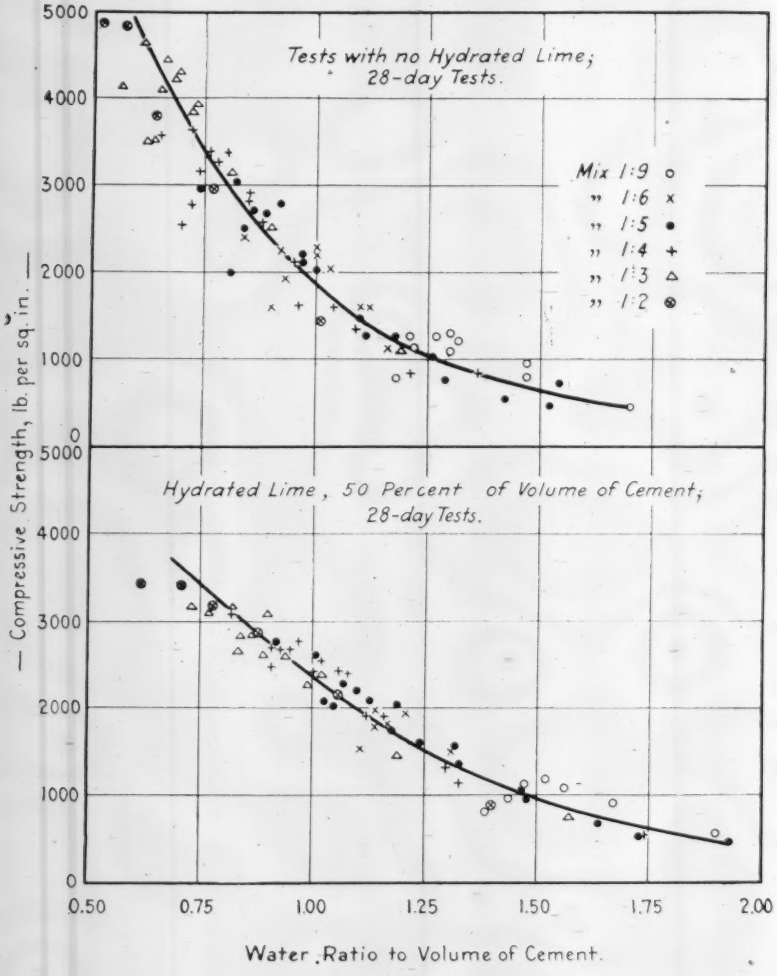


FIG. 7.—Water Ratio - Strength Relation for Concrete With and Without Hydrated Lime.

(Series 130.)

Compression tests of 6 by 12-in. cylinders. Data from Tables IV to VII.

Specimens stored in damp sand; tested damp at age of 28 days.

In platting these curves all water except that absorbed by the aggregate was accredited to the cement; that is, the water absorbed by the hydrated lime was not deducted in calculating the water ratio. For example, the water ratio for a 1 : 4 mix (relative consistency, 1.10, with aggregate of fineness modulus, 5.75), without hydrated lime is 0.78; with 50 per cent hydrated lime it is 1.00. The strength in the first instance is 3100 lb. per sq. in., while with 50 per cent hydrated lime it is 2400 lb. per sq. in. These curves bring out the water ratio - strength relation for a given condition, but do not show directly the effect of hydrated lime on the strength of concrete.

Similar curves may be drawn for other percentages of hydrated lime.

Compare Fig. 10.

of the lean mixes was probably due to the fact that the aggregate was graded too coarse for the quantity of cement; in other words, the admixture slightly improved the *grading* by supplying fine material.

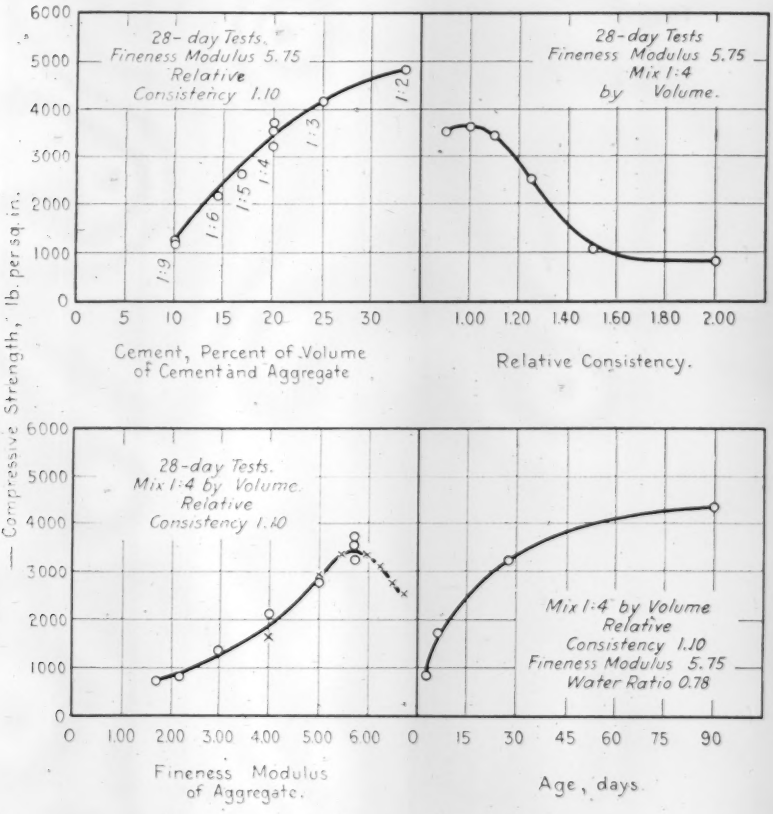


FIG. 8.—Typical Concrete Strength Relations.

(Series 130.)

Compression tests of 6 by 12-in. cylinders. Mix by volume.
Sand and pebble aggregate.
Specimens stored in damp sand; tested damp.
Each value is the average of five or more tests made on different days.
Data from Tables IV to VII.

For the ordinary range of mixes and consistencies (1 : 5 to 1 : 4, and relative consistency 1.00 to 1.25), the strength of the concrete was reduced 0.50 per cent for each 1 per cent of hydrated lime, in terms of volume of cement.

In arriving at this value, richer and leaner mixtures and wetter and dryer mixtures than those indicated were not considered. The following were also excluded on account of not being in the category of ***usual*** concrete mixtures:

(*a*) Concrete of aggregates smaller than $\frac{3}{4}$-in.

(*b*) Aggregates graded to $1\frac{1}{2}$ in., but coarser or finer than is good practice (fineness modulus lower than 5.50 or higher than 6.00 in Table VI).

TABLE XII.—EFFECT OF HYDRATED LIME IN CONCRETE USING A CONSTANT WATER-RATIO.

(Data from Series 114.)

Compression tests of 6 by 12-in. cylinders.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Hydrated lime added to material in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
Sufficient water for normal consistency was used for 50 per cent hydrated lime; the same quantity was used for other percentages, consequently as the percentage of hydrated lime decreased, the concrete was of higher relative consistency.

Hydrated Lime, per cent of cement.		Compressive Strength, lb. per sq. in. (age, 28 days)		
By Volume.	By Weight.	1 : 5 (1.03)[1]	1 : 4 (0.93)[1]	1 : 3 (0.83)[1]
0	0	1990	2140	2640
5	2.2	1710	2320	2570
10	4.5	1990	2110	2560
20	8.9	1970	2410	2470
33	14.7	2170	2410	2610
50	22.3	2080	2260	2560
Average		1980	2280	2570
Minimum value		1710	2110	2470
Maximum value		2170	2410	2640
Mean variation from average, per cent		4.97	4.60	1.49

[1] Water in batch-ratio to volume of cement.

(*c*) Tests in Table X in which cement was replaced by hydrated lime.

(*d*) Tests in Table XI in which a constant quantity of mixing water was used.

Size and Grading of Aggregate.—A distinction is made between *size* and *grading* of aggregate. The size refers to changes in the maximum size with a given type of sieve analysis; grading refers to the type of the sieve analysis curve for a given maximum size. The fineness modulus of the aggregate is used

as a measure of the size and grading. Low values of fineness modulus correspond to finer aggregates; higher values to coarser.

The results of tests from Series 114 and 130 on 1 : 5 and 1 : 4 mixes are given in Table VII. The aggregate ranged in size from 28-mesh sand up to $1\frac{1}{2}$-in. graded aggregate. The percentage change in strength, due to the presence of hydrated lime is given in Table XVII. The finer sands showed a slight increase in strength while the aggregate graded above $\frac{3}{8}$ in. in size showed a decrease in strength with the addition of hydrated lime.

One group of tests was made with aggregates of different gradings in mixes 1 : 9 to 1 : 2; see Table VI and Fig. 5. The different values of fineness modulus were secured by mixing well-graded sand and pebbles (up to $1\frac{1}{2}$ in.) in varying proportions. For the low values of fineness modulus a large percentage of sand was used; for high values the percentage was small. The sand had a fineness modulus of 3.0 and the coarse aggregate a fineness modulus of 7.0; hence, by mixing these materials in different proportions, any value between these limits can be secured. For the usual mixes with aggregates graded up to $1\frac{1}{2}$ in. values of fineness modulus of 5.5 to 6.0 give best results. The change in strength, due to hydrated lime will be found in Table XVIII. For the usual grading and mixes, hydrated lime gave the same reduction in strength noted above from another group of tests; that is, 0.50 per cent for each 1 per cent of hydrated lime. In the finer gradings (low fineness modulus) the strength showed less reduction and for leaner mixtures a slight increase in strength with hydrated lime. A similar relation was found for the very coarse aggregates (fineness modulus 6.50 and 6.75). These results should be compared with those found for fine sands and lean mixes discussed above.

These tests bring out the fact that tests on sand mortars are not a safe guide as to what happens in concrete, since the compression tests of sand mixtures gave a slight increase in strength with the addition of hydrated lime, while the usual concrete mixes show a material reduction in strength.

In Table XI, ten different gradings of aggregate were made up in such a manner as to give a uniform fineness modulus of 6.04, using a 1 : 4 mix at 28 days. Hydrated lime was used in percentages 0, 10, and 33. The mean variation of the tests from

TABLE XIII.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders. Mix 1 : 4 by volume.
Age at test, 28 days.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch: expressed as percentage of *volume* of cement.
Each value is the average of five tests made on different days, unless otherwise noted.

Admixture, per cent of cement by volume.	Compressive Strength for Different Admixtures lb. per sq. in.														
	Brick	Clay.	Fluorspar.	Hydrated Lime.[1]	Kaolin.	Kieselguhr.	Lava.	Limestone.	Natural Cement.[2]	Sand.	Slag.	Tufa.	Whiting.	Yellow Ochre.	Average.
RELATIVE CONSISTENCY, 1.00.															
0[3]	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710	3710
5	3590	3540	3240	3600	3730	3510	3660	3230	3650	3510	3460	3470	3490	3390	3500
10	3700	3520	3450	3580	3620	3440	3770	3640	3320	3420	3810	3420	3560	3600	3560
20	3630	3490	3210	3370	3290	3420	3370	3540	3680	3320	3810	3250	3580	3160	3440
33	3530	3460	3050	3000	2950	3260	3080	3200	3400	3020	3920	3150	3330	2880	3240
50	3430	3260	2600	2700	2730	2900	3000	2780	2990	3040	3850	2720	3160	2360	2970
Average...	3600	3500	3210	3330	3340	3370	3430	3350	3460	3340	3760	3290	3470	3180	3410
RELATIVE CONSISTENCY, 1.10.															
0[3]	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540	3540
5	3420	3510	3230	3320	3380	3310	3280	3340	3350	3190	3400	3200	3360	3560	3340
10	2980	3410	3190	3200	3450	3470	3070	3200	2970	3180	3230	3100	3280	3440	3220
20	3230	3110	2890	2890	3060	3140	3080	3050	2910	3080	3540	2960	3350	2950	3090
33	3350	3000	2740	2600	2830	2710	2760	2640	2820	2890	3520	2720	2970	2650	2880
50	3060	2640	2520	2430	2250	2500	2660	2590	2800	2610	3590	2350	2750	2160	2640
Average...	3260	3200	3020	3000	3080	3110	3060	3060	3060	3080	3470	2980	3210	3040	3120
RELATIVE CONSISTENCY, 1.25.															
0[3]	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600	2600
5	2850	2720	2350	2570	2710	2530	2570	2570	2490	2800	2640	2280	2550	2570	2580
10	2680	2820	2280	2400	2710	2400	2530	2420	2190	2510	2780	2560	2510	2640	2530
20	2810	2650	2390	2340	2530	2380	2420	2480	2200	2430	2700	2330	2560	2370	2470
33	2720	2500	2040	2040	2430	2180	2160	2250	2180	2380	2690	2200	2280	2060	2290
50	2570	2490	2060	1910	1970	1840	2070	2180	1980	2170	2840	2000	2240	1660	2140
Average...	2700	2630	2280	2310	2490	2320	2390	2410	2270	2480	2700	2320	2450	2310	2430
RELATIVE CONSISTENCY, 1.50.															
0[3]	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550	1550
5	1670	1790	1430	1320	1840	1570	1410	1500	1480	1650	1590	1660	1490	1550	1570
10	1610	1710	1420	1440	1730	1550	1470	1480	1530	1500	1540	1410	1540	1510	1530
20	1480	1680	1430	1410	1750	1410	1240	1410	1480	1470	1660	1370	1470	1610	1490
33	1590	1810	1390	1340	1730	1380	1350	1360	1380	1410	1470	1290	1590	1480	1470
50	1710	1700	1230	1140	1480	1230	1230	1300	1120	1270	1600	1160	1540	1170	1350
Average...	1600	1700	1400	1360	1680	1440	1370	1430	1420	1470	1560	1400	1520	1470	1490
GRAND AVERAGE OF ALL CONSISTENCIES.															
0	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850	2850
5	2880	2890	2560	2700	2920	2730	2730	2660	2740	2790	2770	2650	2720	2770	2750
10	2740	2860	2580	2660	2880	2720	2710	2680	2500	2650	2840	2620	2720	2800	2710
20	2790	2730	2480	2500	2660	2590	2530	2620	2570	2580	2930	2480	2740	2520	2620
33	2800	2690	2300	2240	2480	2380	2340	2360	2440	2420	2900	2340	2540	2270	2420
50	2690	2520	2100	2040	2110	2120	2240	2210	2220	2270	2970	2060	2420	1840	2280
Average...	2790	2760	2480	2500	2650	2560	2570	2560	2550	2590	2880	2500	2660	2510	2600

[1] High calcium hydrated lime.
[2] Values for 5 per cent natural cement interpolated.
[3] Average of 10 or 15 tests. The same value is repeated in each column.

TABLE XIV.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders. Mix by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days, unless otherwise noted.

Admixture, per cent of cement by volume.	Mix by Volume.	Age at Test.	High Calcium Hydrated Lime.	High Magnesium Hydrated Lime.	Kaolin.	Kieselguhr.	Limestone.	Natural Cement.	Sand.	Slag.	Tufa.	Whiting.
0	1 : 9	28 days	1260[1]	.....	1220[1]	1220[1]	1220[1]	.....	1220[1]	1220[1]	1220[1]	1220[1]
5			1160[1]	.....	1160	1120	990	.....	1240	1230	1250	1140
10			1190[1]	.....	1230	1140	1040	.....	1130	1190	1100	1160
20			1260[1]	.....	1330	1170	1040	.....	1180	1340	1170	1240
33			1070[1]	.....	1430	1110	1100	.....	1250	1420	1120	1340
50			1190	.....	1430	1170	1120	.....	1210	1510	1170	1360
Average			1190		1300	1160	1080		1200	1320	1170	1240
0	1 : 5	28 days	2670[1]	.....	2670[1]	2670[1]	2670[1]	.....	2670[1]	2670[1]	2670[1]	2670[1]
5			2570	.....	2700	2520	2450	.....	2450	2460	2490	2420
10			2560	.....	2670	2490	2540	.....	2500	2580	2440	2630
20			2430	.....	2620	2450	2490	.....	2370	2730	2510	2580
33			2350	.....	2310	2260	2420	.....	2230	2610	2270	2600
50			2200	.....	2280	2140	2270	.....	2080	2640	2000	2410
Average			2460		2540	2420	2470		2380	2620	2400	2550
0	1 : 4	28 days	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]	3540[1]
5			3320	3350	3380	3310	3340	3400[2]	3190	3400	3200	3360
10			3200	3240	3450	3470	3200	2970	3180	3230	3100	3280
20			2890	3180	3060	3140	3050	2910	3080	3540	2960	3350
33			2600	2650	2830	2710	2640	2820	2890	3520	2720	2970
50			2430	2380	2250	2500	2590	2800	2610	3590	2350	2750
Average			3000	3060	3080	3110	3060	3070	3080	3470	2980	3210
0	1 : 3	28 days	4200[1]	.....	4200[1]	4200[1]	4200[1]	.....	4200[1]	4200[1]	4200[1]	4200[1]
5			3780	.....	3520	4110	3830	.....	3760	3800	2650	3620
10			3780	.....	3550	3630	3700	.....	3580	3780	3600	3680
20			3300	.....	3230	3330	3620	.....	3370	3670	3230	3520
33			3080	.....	2930	3220	3530	.....	3190	3650	2900	3250
50			2590	.....	2570	2760	2900	.....	2850	3440	2630	3090
Average			3460		3330	3540	3630		3490	3760	3200	3560
0	1 : 4	3 days	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]	1030[1]
5			990	1100	1040	920	1050	1100[2]	1050	1030	1080	1120
10			960	1050	1110	950	1050	1080	1100	1020	960	1060
20			830	1020	1040	870	1140	1080	1060	1020	950	1090
33			740	910	990	710	1110	1050	1080	1020	820	1060
50			890	900	830	700	1010	960	980	950	690	1060
Average			910	1000	1010	860	1060	1050	1050	1010	920	1070
0	1 : 4	7 days	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]	1860[1]
5			1720	1850	1950	1760	1790	1850[2]	1850	1890	1630	1770
10			1880	1820	1910	1550	2030	1850	1730	1620	1730	1800
20			1690	1770	1870	1500	1780	1720	1660	1920	1690	1760
33			1590	1660	1570	1380	1740	1620	1700	1820	1450	1700
50			1440	1360	1420	1180	1500	1610	1470	1760	1300	1550
Average			1690	1720	1760	1530	1780	1750	1710	1810	1610	1740
0	1 : 4	3 mo.	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]	4370[1]
5			4050	4390	4220	4240	3980	4260[2]	4360	4210	4260	4160
10			4270	4240	4130	4260	4200	4130	4260	4260	4140	3990
20			3760	3750	3730	3560	4000	4110	4030	4460	4080	3780
33			3540	3490	3390	3390	3640	3950	3480	4630	3940	3680
50			3260	3090	2640	3040	3360	3640	3280	4600	3730	3600
Average			3880	3890	3750	3810	3920	4080	3960	4420	4090	3930

[1] Average of 10 or 15 tests.
[2] Values for 5 per cent natural cement obtained by interpolation.

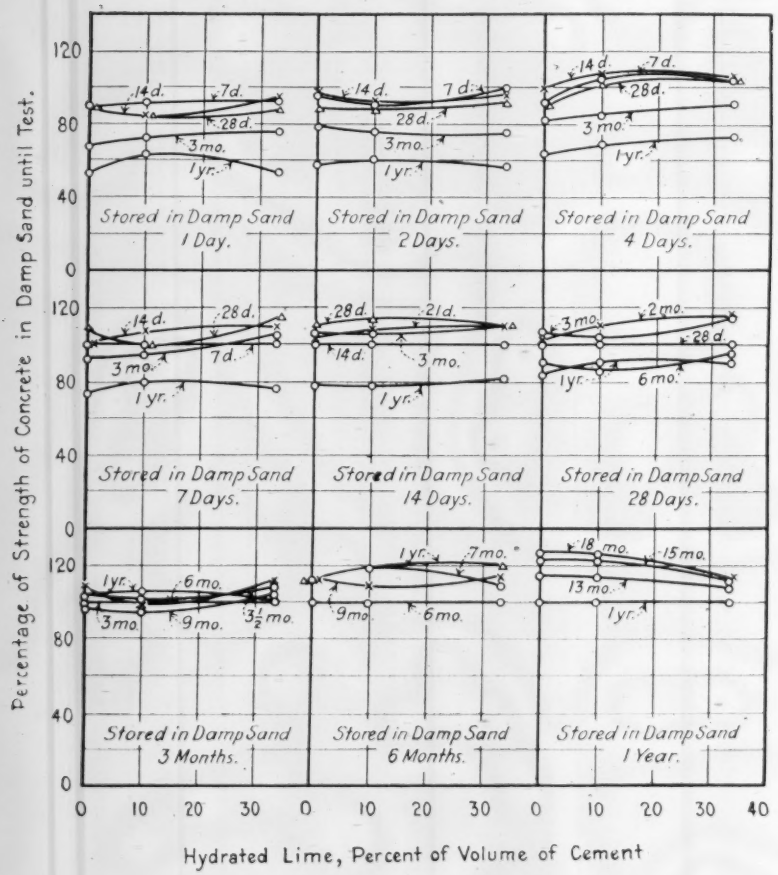

Percentage of Strength of Concrete in Damp Sand until Test.
Hydrated Lime, Percent of Volume of Cement
Stored in Damp Sand 1 Day.
Stored in Damp Sand 2 Days.
Stored in Damp Sand 4 Days.
Stored in Damp Sand 7 Days.
Stored in Damp Sand 14 Days.
Stored in Damp Sand 28 Days.
Stored in Damp Sand 3 Months.
Stored in Damp Sand 6 Months.
Stored in Damp Sand 1 Year.
14 d.
7 d.
28 d.
3 mo.
1 yr.
21 d.
2 mo.
6 mo.
9 mo.
18 mo.
15 mo.
13 mo.
7 mo.
3½ mo.

FIG. 9.—Effect of Hydrated Lime on the Strength of Concrete Cured under Different Conditions.

(Series 114.)

Values expressed as percentages of strength of concrete stored in damp sand until tested. Specimens stored in damp sand for periods indicated; remainder of time in air until tested at ages noted on curves.

Compression tests of 6 by 12-in. cylinders. Mix, 1 : 4 by volume.

Sand and pebble aggregate, graded 0–1½ in., fineness modulus, 5.75.

Relative consistency of concrete, 1.00.

Each value is the average of five tests made on different days.

Data from Table IX.

the average is 4.2 per cent, indicating a practically uniform strength regardless of the widest variation in the grading of the aggregate. The tests with and without hydrated lime showed

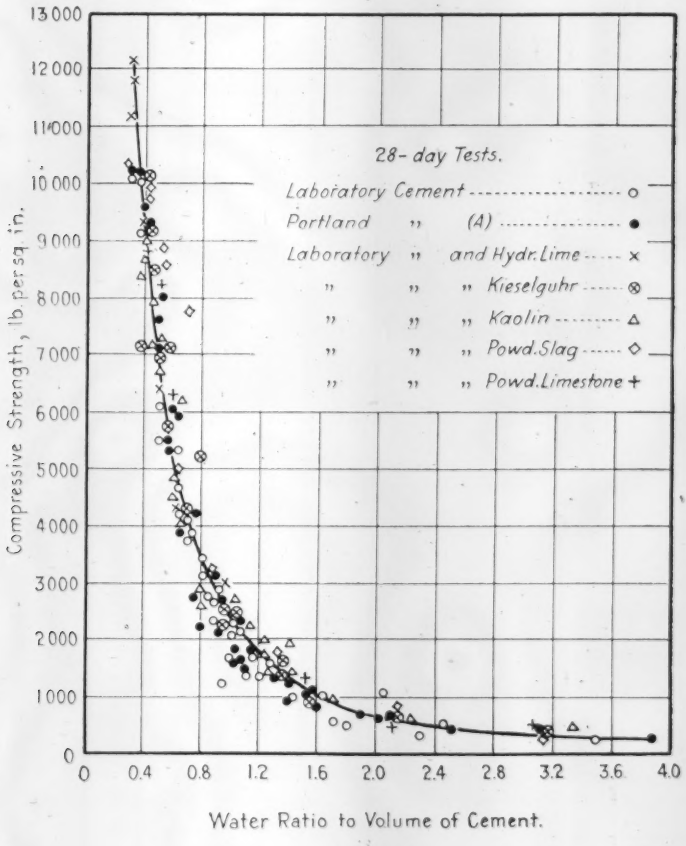


FIG. 10.—Effect of Water on the Strength of Concrete.

(Series 100)

Compression tests of 2 by 4-in. cylinders, neat and 1 : 3 mixes.
Specimens stored in water; tested damp at age of 28 days.
Details of these tests are not reported. Similar data are on hand from tests at 7 days, 3 months and 1 year. Compare Fig. 7.

the same relation so far as grading of aggregate is concerned. However, the strength was reduced in all cases due to the presence of hydrated lime. The reduction in strength was 0.50 per cent for each 1 per cent hydrated lime.

High Magnesium versus High Calcium Hydrated Lime.—Most of the tests were made with high calcium lime; in Series 130 high magnesium hydrated lime was also used. Compression tests of 1 : 4 concrete were made at ages of 3 days to 3 months; 1-year tests are not due. Both types of hydrated lime gave the same results; the values in many instances were almost identical; see Tables XIV and XIX.

Curing Condition.—The effect of hydrated lime on the strength of concrete cured under different conditions is shown in Table IX and Fig. 9. Tests were made on a 1 : 4 mix, using 0, 10 and 33 per cent hydrated lime. Specimens were stored in damp sand for periods ranging from 1 day to 1 year, after which they were stored in air until tested at ages ranging from 7 days to 18 months. The actual strengths were also reduced to percentages of the strength of the concrete stored in damp sand through the entire curing period. If the presence of hydrated lime had a beneficial influence on the strength of concrete stored in air subsequent to the period stored in damp sand, the curves in Fig. 9 should show an upward trend. In general these curves are practically horizontal or show only a slight upward trend, indicating that hydrated lime was of no material benefit in raising the relative strength; while the actual strength was in general reduced by hydrated lime. In this group of tests care must be taken to distinguish between the *curing period* and the *age at test.* The discussion below on the evaporation and absorption also throws interesting light on this phase of the effect of hydrated lime in concrete.

Evaporation and Absorption.—In order to determine the effect of hydrated lime and other admixtures on the evaporation and absorption of water, careful weights were made on the wear blocks in Series 130. The results of wear tests are given in Tables XX and XXI.

The results of evaporation and absorption tests are given in Fig. 13. The evaporation was determined by weighing the blocks upon removal from damp sand at the age of 14 days and at intervals up to the time they were tested at the age of 3 months. The tests show that all the admixtures gave essentially the same results; that evaporation occurred more rapidly in the leaner mixes than in the richer ones, and that the evaporation

TABLE XV.—EFFECT OF POWDERED ADMIXTURES ON THE STRENGTH OF CONCRETE.

(Data from Series 130.)

Compression tests of 6 by 12-in. cylinders.
Mix 1 : 4 by volume. Relative consistency, 1.10.
Aggregates: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand; tested damp.
Each value is the average of five tests made on different days.
The 1-year tests are not due.

Admixture, per cent of cement, by volume.	Water, ratio to volume of cement.					Compressive Strength, lb. per sq. in.				
	Hydrated Lime.	Gypsum.	Mica.	Pitch.	Ironite.	Hydrated Lime.	Gypsum.	Mica.	Pitch.	Ironite.
AGE AT TEST, 3 DAYS.										
0[1]	0.78	0.78	0.78	0.78	0.78	1030	1030	1030	1030	1030
1	0.78	0.79	0.78	0.79	0.78	....	1290	1140	1110	1120
2	0.79	0.79	0.78	0.79	0.79	....	1270	1070	1030	1100
5	0.80	0.81	0.78	0.80	0.80	990	650	1110	1050	1170
10	0.83	0.83	0.78	0.82	0.81	960	470	1120	950	1070
20	0.87	0.88	0.78	0.87	....	830	420	970	800	....
						Av. 1170	860	1070	1000	1100
AGE AT TEST, 7 DAYS.										
0[1]	0.78	0.78	0.78	0.78	0.78	1860	1860	1860	1860	1860
1	0.78	0.79	0.78	0.79	0.78	....	1850	1830	1850	1840
2	0.79	0.79	0.78	0.79	0.79	....	1900	1860	1910	1810
5	0.81	0.81	0.78	0.80	0.80	1720	810	1860	1760	1700
10	0.83	0.83	0.78	0.82	0.81	1880	640	1860	1570	1600
20	0.88	0.88	0.78	0.87	....	1690	570	1520	1300	....
						Av. 1810	1270	1800	1710	1760
AGE AT TEST, 28 DAYS.										
0[1]	0.78	0.78	0.78	0.78	0.78	3540	3540	3540	3540	3540
1	0.78	0.79	0.78	0.79	0.78	....	3440	3270	3490	3280
2	0.79	0.79	0.78	0.79	0.79	....	3350	3570	3120	3230
5	0.81	0.81	0.78	0.80	0.80	3320	2830	3330	3130	3120
10	0.83	0.83	0.78	0.82	0.81	3200	980	3420	3050	3220
20	0.88	0.88	0.78	0.87	....	2890	860	2710	2590	....
						Av. 3320	2500	3310	3150	3280
AGE AT TEST, 3 MONTHS.										
0[1]	0.78	0.78	0.78	0.78	0.78	4370	4370	4370	4370	4370
1	0.78	0.79	0.78	0.79	0.78	....	4420	4290	4500	4050
2	0.79	0.79	0.78	0.79	0.79	....	4330	4370	4480	4390
5	0.81	0.81	0.78	0.80	0.80	4050	4080	4190	4120	4310
10	0.83	0.83	0.78	0.82	0.81	4270	1230	4050	4000	4090
20	0.88	0.88	0.78	0.87	....	3760	800	3200	3390	....
						Av. 4180	3200	4080	4140	4240

[1] Average of 10 tests.

TABLE XVI.—EFFECT OF HYDRATED LIME ON THE PLASTICITY OF CONCRETE.

(Data from Series 130.)

Slump tests of 6 by 12-in. concrete cylinders.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Cement: a mixture of five brands purchased in the Chicago market.
Admixture added to cement.
Each value is the average of five tests made on different days.

Admixture, per cent of cement.		Slump of Concrete for Different Relative Consistencies, in.						
By Volume.	By Weight.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
				MIX 1 : 9 BY VOLUME.				
0	0	4.6	6.2	2.1	1.5	...	...	...
5	2.1	4.5	2.6	0.3	0.2	...	...	...
10	4.2	4.7	1.5	1.5	1.5	...	...	...
20	8.5	4.8	1.7	0.2	1.6	...	...	...
33	14.0	0.6	0.2	0.3	4.0	...	...	...
		Av. 3.8	2.4	0.9	1.8			
				MIX 1 : 6 BY VOLUME.				
0	0	1.7	0.3	2.0	4.0	...	...	...
5	2.1	3.1	0.3	3.0	5.5	...	...	...
10	4.2	1.4	0.3	1.8	5.6	...	...	...
20	8.5	0.2	0.5	2.1	7.8	...	...	...
33	14.0	0.3	0.5	5.0	7.8	...	...	...
		Av. 1.3	0.4	2.8	6.1			
				MIX 1 : 5 BY VOLUME.				
0	0	0.2	0.3	2.0	6.7	7.5	8.6	4.2
5	2.1	1.1	0.4	4.0	7.8	6.9	8.6	5.0
10	4.2	0.1	0.5	5.8	7.4	8.5	7.6	5.0
20	8.5	0.2	2.2	5.0	5.7	8.4	9.0	5.1
33	14.0	0.2	1.9	6.1	8.0	9.0	9.2	5.7
50	21.3	0.3	1.9	6.8	8.6	9.6	10.0	6.2
		Av. 0.4	1.2	5.1	7.4	8.3	8.8	5.2

TABLE XVI.—EFFECT OF HYDRATED LIME ON THE PLASTICITY OF CONCRETE.—*Continued.*

Admixture, per cent of cement.		Slump of Concrete for Different Relative Consistencies, in.						
By Volume.	By Weight.	0.90	1.00	1.10	1.25	1.50	2.00	Average.
				MIX 1 : 4 BY VOLUME.				
0	0	1.2	0.7	6.1	6.8	7.4	8.7	5.2
5	2.1	0.1	1.2	6.8	8.2	8.9	8.7	5.6
10	4.2	0.2	2.0	5.9	8.3	9.0	9.2	5.8
20	8.5	1.5	3.1	6.4	8.3	9.4	9.4	6.4
33	14.0	0.4	3.1	7.2	8.9	9.1	9.5	6.4
50	21.3	0.3	1.4	6.1	8.6	9.4	10.0	6.0
		Av. 0.6	1.9	6.4	8.2	8.9	9.3	5.9
				MIX 1 : 3 BY VOLUME.				
0	0	0.2	4.2	6.5	8.3	9.3	9.8	6.4
5	2.1	0.2	1.7	6.3	8.7	9.2	7.9	5.7
10	4.2	0.3	2.3	6.6	8.4	9.0	9.8	6.1
20	8.5	1.2	3.0	6.4	8.5	9.5	9.9	6.4
33	14.0	0.3	3.3	6.5	8.4	9.6	10.0	6.4
50	21.3	0.3	2.4	6.2	8.8	9.8	10.1	6.3
		Av. 0.4	2.8	6.4	8.5	9.4	9.6	6.2
				MIX 1 : 2 BY VOLUME.				
0	0	0.2	1.2	6.8	8.8	9.4	9.8	6.0
5	2.1	0.4	3.0	6.6	9.1	9.9	9.9	6.5
10	4.2	0.4	2.1	7.1	9.1	10.0	10.4	6.5
20	8.5	0.2	2.1	5.5	8.7	9.8	10.1	6.1
33	14.0	0.2	1.0	5.1	8.3	9.8	10.4	5.8
50	21.3	0.1	0.9	4.8	8.1	9.9	10.6	5.7
		Av. 0.3	1.7	6.0	8.7	9.8	10.2	6.1
				AVERAGE OF 1 : 5, 1 : 4, 1 : 3 AND 1 : 2 MIXES.				
0	0	0.4	1.6	5.4	7.6	8.4	9.2	5.5
5	2.1	0.4	1.6	6.2	8.4	8.7	8.8	5.7
10	4.2	0.2	1.7	6.4	8.3	9.1	9.2	5.8
20	8.5	0.8	2.6	5.8	7.8	9.3	9.6	6.0
33	14.0	0.3	2.3	6.2	8.4	9.4	9.8	6.1
50	21.3	0.2	1.6	6.0	8.5	9.7	10.2	6.0
		Av. 0.4	1.9	6.0	8.2	9.1	9.5	5.8

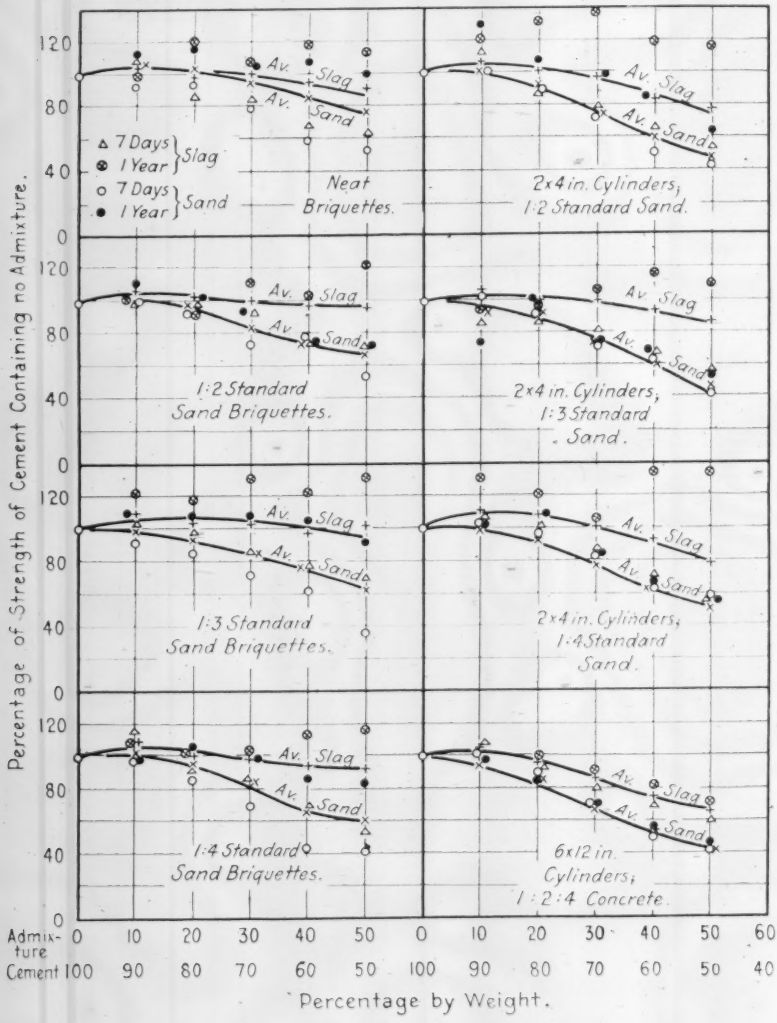

Percentage of Strength of Cement Containing no Admixture.
△ 7 Days } Slag
⊗ 1 Year }
○ 7 Days } Sand
● 1 Year }
Av. Slag
Av. Sand
Neat Briquettes.
2×4 in. Cylinders, 1:2 Standard Sand.
1:2 Standard Sand Briquettes.
2×4 in. Cylinders, 1:3 Standard Sand.
1:3 Standard Sand Briquettes.
2×4 in. Cylinders, 1:4 Standard Sand.
1:4 Standard Sand Briquettes.
6×12 in. Cylinders, 1:2:4 Concrete.
Admixture
Cement
0 10 20 30 40 50 0 10 20 30 40 50 60
100 90 80 70 60 50 100 90 80 70 60 50 40
Percentage by Weight.

FIG. 11.—Relative Strengths of Sand and Slag Cements.

(Series 58.)

Values are expressed as percentages of the strength of mortar or concrete using Portland cement without admixture.

Sand or slag was added to the cement prior to final grinding.

For mortar strength and miscellaneous tests of sand and slag cements, see Table I.

Mortar specimens stored in water; tested wet.

Concrete specimens stored in damp sand; tested damp.

Points shown for 7-day and 1-year tests only. The average is from 7-day, 28-day, 3-month, 6-month and 1-year tests.

Each value is the average of four tests made on different days.

Further details of these tests are not reported.

Compare Figs. 6 and 12.

was slightly more rapid with hydrated lime than without, although there was little difference for quantities of hydrated lime less than 10 per cent. The blocks gained slightly in weight during the storage in damp sand. After storage for 10 weeks in air they showed a loss in weight of about $2\frac{1}{2}$ per cent—equivalent to 25 to 30 per cent of the original mixing water.

Bond Tests.—Tests of bond between concrete and steel were carried out in Series 104. The results of parallel bond and compression tests on a 1 : 5 mix, using hydrated lime up to 50 per cent, are given in Table X. It should be noted that in this series the hydrated lime *replaced* an equal volume of cement; consequently the quantity of cement decreased as the percentage

TABLE XVII.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

(Effect of Size of Aggregate—Series 114 and 130.)

Compression tests of 6 by 12-in. concrete cylinders.
28-day tests of hand-mixed concrete.
Reduction in strength calculated from slope of curves drawn from data in Table VII.
Compare Tables XVIII and XIX.

Series.	Mix, by Volume.	Relative Consistency.	Percentage Reduction in Strength for Each 1 per cent Hydrated Lime, in terms of volume of Cement.						
			0 to No. 28	0 to Nos 14	0 to No. 8	0 to No. 4	0 to $\frac{3}{8}$ in.	0 to $\frac{3}{4}$ in.	0 to $1\frac{1}{2}$ in.
114	1 : 4	1.00	.....	+0.21	+0.18	+0.32	0.20	0.64	0.58
130	1 : 4	1.10	+0.44	+0.24	.....	0	0.22	0.32	0.60
130	1 : 5	1.10	+0.22	+0.54	.....	0	+0.06	0.50	0.34

NOTE.—+ indicates increase in strength.

of hydrated lime increased. This arrangement, of course, gave a much greater reduction in strength due to hydrated lime than was found in the tests in which the hydrated lime was added to a constant volume of cement. The bond resistance was affected in the same manner by the addition of hydrated lime as the compressive strength.

Density and Yield.—The density and yield of concrete were determined for all conditions. It is impracticable to give all of the results of these tests. However, the general trend of the values may be seen from Tables XXII and XXIII.

The density was calculated from the dimensions of the specimens, the volumes of materials used in the batch and the unit weight of the concrete. The density may be defined as the

ratio of the total volume of solids in the mass to the volume of concrete. It will be noted that the maximum density was produced by the leaner mixes. As the proportion of cement increased the density was reduced. The density was also materially reduced by increasing the water content. Density was slightly reduced by the addition of hydrated lime; the addition of 50 per cent of hydrated lime to a 1 : 4 mix, consistency 1.10, reduced the density about 4 per cent.

TABLE XVIII.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

(Effect of Consistency and Grading of Aggregate.)

Compression tests of 6 by 12-in. concrete cylinders.
Reduction in strength calculated from average slope of curves in figures indicated.
Age at test 28 days.
Compare Tables XVII and XIX.

Relative Consistency.	Aggregate.		Age at Test, days.	Percentage Reduction in Strength for Each 1 per cent Hydrated Lime in terms of volume of cement.						Values Calculated from
	Size, in.	Fineness Modulus.[1]		1 : 9	1 : 6	1 : 5	1 : 4	1 : 3	1 : 2	Average.	
0 90	0 - 1½	5 75	28	+0 12	+0 12	0 10	0 38	0 54	0 62	0 41[3]	Fig. 3
1 00				0	0	0 28	0 48	0 58	0 60	0 48[3]	
1 10				0 15	0 25	0 32	0 60	0 68	0 66	0 56[3]	
1 25				0	0 42	0 48	0 62	0 64	0 60	0 58[3]	
1 50						0 56	0 56	0 64	0 66	0 60[3]	
2 00						0 72	0 62	0 70	0 66	0 68[3]	
				[4]Av. 0 01	0 14	0 29	0 52	0 61	0 62	0 56	
1 10	0 - 1½	4 00	28	+0 04	0	0	0	0 40		0 07	Fig. 5
		5 00		+0 12	0 12	0 16	0 42	0 70		0 25[3]	
		5 50		0	0	0 52	0 48	0 66		0 32	
		5 75		0 34	0 30	0 36	0 56	0 76		0 46	
		6 00		0 24	0 32	0 28	0 44	0 64		0 38	
		6 25		0 22	0 20	0 32	0 38	0 64		0 35	
		6 50		0 12	0	0	0 20	0 42		0 14	
		6 75[2]		....	....	....	0	0 44	....	....	
				Av. 0 11	0 14	0 24	0 35	0 61	....	0 29	

NOTE.—+ indicates increase in strength.

[1] Fineness modulus of aggregate: the sum of the percentages in the seive analysis, divided by 100. See Table II for seive analysis of aggregates.
[2] Omitted from average.
[3] Mixes 1 : 9 and 1 : 6 omitted from average.
[4] Relative consistencies 1.50 and 2.00 omitted from average.

The yield expresses the volume of finished concrete in terms of the volume of mixed aggregate as used.

The yield of concrete increased with the addition of powdered materials. The richer mixes were more affected than the leaner ones. For mixtures richer than 1:6, hydrated lime increased the volume of concrete 50 to 60 per cent of the volume of loose lime added. For other materials the increase in volume

(yield) appears to be proportional to the total volume of solid material in the admixture.

Plasticity of Concrete.—In Series 130 the plasticity of the concrete was measured by means of the slump test described above. A high value of slump indicates a more plastic concrete than a low one. Table XVI gives the results of one group of

TABLE XIX.—REDUCTION IN STRENGTH OF CONCRETE BY HYDRATED LIME.

Compression tests of 6 by 12-in. concrete cylinders.
Reduction in strength calculated from average slope of curves in figures indicated.
Compare Tables XVII and XVIII.

Mix, by Volume.	Relative Consistency.	Aggregate.		Percentage Reduction in Strength for Each 1 per cent Hydrated Lime, in terms of volume of cement.						Values Calculated from
		Size, in.	Fineness Modulus.	3 days.	7 days.	28 days.	3 mo.	1 year.	Average.	
1 : 4	0.90	0 - 1½	5.75	....	0.52	0.56	0.54	0.54	0.54	Fig. 1
	0.95			....	0.50	0.50	0.54	0.50	0.52	
	1.00			....	0.62	0.66	0.60	0.44	0.58	
	1.05			....	0.42	0.50	0.56	0.50	0.50	
	1.10			....	0.40	0.68	0.52	0.40	0.50	
	1.25			....	0.44	0.60	0.52	0.32	0.48	
	1.50			....	0.46	0.52	0.66	0.66	0.58	
	2.00			....	0.74	0.74	0.56	0.58	0.66	
				Av.	0.52	0.56	0.56	0.50	0.54	
1 : 9	1.00	0 - 1½	5.75	....	+0.82	+0.18	+0.12	+0.24	+0.34	Fig. 2
1 : 6				....	....	0.14[1]	....	....	....	
1 : 5				....	0	0.50	0.52	0.46	0.37	
1 : 4				....	0.58	0.60	0.62	0.40	0.55	
1 : 3				....	0.85	0.60	0.55	0.61	0.65	
1 : 2				....	....	0.66[1]	....	....	....	
				Av.	0.15	0.38	0.39	0.31	0.31	
1 : 9	1.10	0 - 1½	5.75	0.22	0.16	0.15	0	....	0.13	Fig. 4
1 : 6				0.24	0.12	0.25	0.36	....	0.24	
1 : 5				0.26	0.22	0.32	0.44	....	0.31	
1 : 4				0.30	0.40	0.60	0.52	....	0.45	
1 : 3				0.40	0.58	0.68	0.46	....	0.53	
1 : 2				0.64	0.72	0.66	0.52	....	0.63	
				Av. 0.34	0.36	0.44	0.38	....	0.38	
1 : 4[2]	1.10	0 - 1½	5.75	0.30	0.40	0.60	0.52	....	0.46	Table XV
1 : 4[3]				0.36	0.52	0.62	0.62	....	0.52	
				Av. 0.33	0.46	0.61	0.57	....	0.49	

NOTE. — + indicates increase in strength.
[1] Omitted from average.
[2] High calcium hydrated lime.
[3] High magnesium hydrated lime.

tests in which the mix and consistency were varied. The slump was only slightly affected by the presence of hydrated lime up to 50 per cent in the usual concrete mixtures. In the leaner mixes the slump was in general increased by the addition of hydrated lime. For the richer mixes the slump was decreased.

Addition versus Replacement.—Fig. 6 gives the relative strength of concrete for different mixtures and percentages of lime. This figure is based on tests in which hydrated lime was added to the cement. The curves in the upper right corner illustrate the method of calculating the effect of replacing cement by hydrated lime. In general the reduction in strength caused by replacing cement by hydrated lime was about $1\frac{3}{4}$ times that caused by adding hydrated lime to cement.

MISCELLANEOUS POWDERED ADMIXTURES IN CONCRETE.

In addition to hydrated lime, compression tests of concrete were made on 17 different powdered admixtures; see Table III.

TABLE XX.—EFFECT OF POWDERED ADMIXTURES ON THE WEAR OF CONCRETE.

(Data from Series 130.)

Wear tests of 8 by 8 by 5-in. blocks. Mix, 1 : 4 by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.
Powdered admixture added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand 14 days, remainder in air. Age at test 3 months.
Wear tests made in Talbot-Jones rattler.
Each value is the average of 15 tests made in groups of five on three different days, unless otherwise noted.

Admixture, per cent of cement by volume.	Wear for Different Admixtures, in.						
	Hydrated Lime (High Calcium).[1]	Kieselguhr.	Powdered Limestone.	Powdered Slag.	Powdered Sand.	Natural Cement.	Average.
0[2]	0.40	0.40	0.40	0.40	0.40	0.40	0.40
5	0.36	0.41	0.45	0.41	0.36	0.38	0.40
10	0.40	0.43	0.45	0.42	0.42	0.38	0.42
20	0.45	0.43	0.41	0.36	0.39	0.44	0.41
33	0.49	0.52	0.42	0.39	0.38	0.42	0.44
Average	0.42	0.44	0.43	0.40	0.39	0.40	0.41

[1] Values from 1 : 4 mix in Table XXI.
[2] Average of 30 tests made in groups of five on six different days. The same value is repeated in each column.

The results of compression tests are given in Tables XII to XIV. Wear tests were also made with a portion of these admixtures; see Tables XX and XXI. For compression tests of mortars of miscellaneous admixtures made in Series 100; see Fig. 10.

In studying the effect of admixtures, curves were platted showing the relation between the strength of concrete and percentage of material added; see Figs. 1 to 5. In general these curves are essentially straight lines, consequently the slope represents the rate of change of strength with the percentages of admixtures. Most of these admixtures gave essen-

tially the same results and showed the same effect as hydrated lime. Usual concrete mixtures were reduced in strength. The only exception to this statement is pulverized blast furnace slag. Gypsum gave a much greater reduction in strength than any of the other materials.

Brick.—Common building brick from the Chicago district, crushed and pulverized, was used. The tests showed that the strength of 1 : 4 concrete at 28 days was reduced 0.08 per cent for each 1 per cent addition of powdered brick in terms of the volume of cement.

TABLE XXI.—EFFECT OF HYDRATED LIME ON THE WEAR OF CONCRETE.

(Data from Series 130.)

Wear tests of 8 by 8 by 5-in. blocks.
Mix by volume. Relative consistency, 1.10.
Aggregate: sand and pebbles from Elgin, Ill., graded 0-1½ in., fineness modulus 5.75.
Hydrated lime added to materials in batch; expressed as percentage of *volume* of cement.
Specimens stored in damp sand 14 days; remainder in air.
Age at test, 3 months.
Wear tests made in Talbot-Jones rattler.
Each value is the average of 15 tests, made in groups of five, on three different days, unless otherwise noted.

Hydrated Lime, per cent of cement by volume.	Wear for Different Mixtures, in.					
	1 : 4½	1 : 4	1 : 3½	1 : 3	1 : 2½	Average.
0	0.40	0.40	0.38	0.38	0.34	0.38
5	0.39	0.36	0.39	0.37	0.33	0.37
10	0.39	0.40	0.38	0.39	0.36	0.38
20	0.46	0.45	0.40	0.40	0.38	0.42
33	0.48	0.49	0.41	0.46	0.44	0.46
Average	0.42	0.42	0.39	0.40	0.37	0.40

[1] Average of 30 tests made in groups of five on six different days.

Clay.—The clay used was a light fluffy material from South Amboy, N. J. The strength of concrete was reduced 0.22 per cent for each 1 per cent of this material.

Fluorspar.—The fluorspar was obtained from a mine at Shawneetown, Ill. Concrete strength was reduced 0.43 per cent.

Gypsum.—A first-settle gypsum without retarder was used. The strength was slightly increased by 1 or 2 per cent of gypsum at ages of 3 and 7 days. The reduction in strength was very pronounced for quantities higher than 5 per cent at all ages. The average reduction was about 4 per cent for each 1 per cent of gypsum.

Hydrated Lime.—Under the same conditions as used in tests

TABLE XXII.—EFFECT OF HYDRATED LIME ON THE YIELD AND DENSITY OF CONCRETE.

(Data from Series 130.)

6 by 12-in. cylinders.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.

Admixture added to materials in batch; expressed as percentage of *volume* of cement.

Yield is the volume of concrete produced by one volume of mixed aggregate.

Density is the total solid material in the mass.

Yield and density were calculated from weights determined immediately on removal of the cylinders from the forms. See Table XXIII for other data on yield and density.

See Table IV for water-ratio and strength tests.

Hydrated Lime, per cent of cement.		For Different Relative Consistencies.											
		Yield of Concrete.						Density of Concrete.					
By Volume.	By Weight.	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
MIX 1 : 9 BY VOLUME.													
0	0	0.988	0.992	0.991	0.985	.....	.....	0.834	0.831	0.832	0.837	.....	.....
5	2.1	0.997	0.995	0.979	0.993	.....	.....	0.828	0.826	0.843	0.832	.....	.....
10	4.2	0.998	0.997	1.002	1.009	.....	.....	0.829	0.829	0.825	0.829	.....	.....
20	8.5	0.984	0.983	0.987	0.997	.....	.....	0.843	0.844	0.840	0.832	.....	.....
33	14.0	0.997	0.995	1.000	1.009	.....	.....	0.837	0.838	0.835	0.828	.....	.....
Average.....		0.993	0.992	0.992	0.999	.....	.....	0.834	0.834	0.835	0.832	.....	.....
MIX 1 : 6 BY VOLUME.													
0	0	1.016	1.003	1.008	1.023	.....	.....	0.838	0.847	0.845	0.831	.....	.....
5	2.1	1.013	1.011	1.016	1.026	.....	.....	0.841	0.844	0.840	0.832	.....	.....
10	4.2	1.017	1.016	1.021	1.030	.....	.....	0.842	0.843	0.838	0.831	.....	.....
20	8.5	1.023	1.023	1.030	1.044	.....	.....	0.840	0.840	0.835	0.823	.....	.....
33	14.0	1.026	1.031	1.038	1.053	.....	.....	0.845	0.840	0.835	0.822	.....	.....
Average.....		1.019	1.017	1.023	1.015	.....	.....	0.841	0.843	0.839	0.828	.....	.....
MIX 1 : 5 BY VOLUME.													
0	0	1.040	1.032	1.032	1.049	1.062	1.106	0.833	0.839	0.839	0.826	0.816	0.784
5	2.1	1.037	1.031	1.043	1.053	1.067	1.120	0.839	0.843	0.833	0.825	0.815	0.777
10	4.2	1.050	1.043	1.048	1.056	1.080	1.120	0.832	0.837	0.833	0.827	0.808	0.779
20	8.5	1.043	1.043	1.056	1.067	1.090	1.137	0.842	0.842	0.833	0.824	0.806	0.773
33	14.0	1.055	1.061	1.075	1.092	1.110	1.161	0.840	0.835	0.824	0.811	0.798	0.763
50	21.3	1.083	1.090	1.096	1.116	1.144	1.181	0.827	0.822	0.818	0.803	0.783	0.758
Average.....		1.051	1.050	1.058	1.072	1.092	1.138	0.836	0.836	0.830	0.819	0.804	0.772
MIX 1 : 4 BY VOLUME.													
0	0	1.063	1.063	1.077	1.094	1.110	1.151	0.837	0.837	0.828	0.814	0.802	0.774
5	2.1	1.069	1.076	1.082	1.099	1.126	1.160	0.837	0.832	0.827	0.815	0.795	0.772
10	4.2	1.068	1.082	1.089	1.106	1.130	1.174	0.841	0.830	0.825	0.812	0.795	0.764
20	8.5	1.076	1.092	1.107	1.125	1.144	1.199	0.842	0.828	0.818	0.804	0.790	0.755
33	14.0	1.111	1.120	1.129	1.140	1.178	1.217	0.823	0.817	0.810	0.802	0.777	0.752
50	21.3	1.136	1.153	1.163	1.183	1.207	1.241	0.816	0.802	0.796	0.782	0.767	0.746
Average.....		1.087	1.098	1.108	1.124	1.149	1.190	0.833	0.824	0.817	0.805	0.788	0.760

TABLE XXII.—EFFECT OF HYDRATED LIME ON THE YIELD AND DENSITY OF CONCRETE.—*Continued.*

Hydrated Lime, per cent of cement.		For Different Relative Consistencies.											
		Yield of Concrete.						Density of Concrete.					
By Volume	By Weight.	0.90	1.00	1.10	1.25	1.50	2.00	0.90	1.00	1.10	1.25	1.50	2.00
MIX 1 : 3 BY VOLUME.													
0	0	1.140	1.132	1.142	1.160	1.187	1.236	0.817	0.823	0.817	0.803	0.786	0.754
5	2.1	1.148	1.140	1.156	1.176	1.203	1.246	0.816	0.822	0.810	0.797	0.778	0.752
10	4.2	1.147	1.154	1.162	1.182	1.211	1.262	0.822	0.815	0.810	0.796	0.777	0.746
20	8.5	1.168	1.176	1.185	1.205	1.238	1.294	0.814	0.809	0.802	0.788	0.768	0.734
33	14.0	1.209	1.203	1.221	1.242	1.277	1.328	0.797	0.800	0.789	0.775	0.755	0.726
50	21.3	1.241	1.238	1.256	1.278	1.306	1.380	0.789	0.791	0.780	0.767	0.750	0.710
Average		1.176	1.174	1.187	1.207	1.237	1.291	0.809	0.810	0.801	0.788	0.769	0.737
MIX 1 : 2 BY VOLUME.													
0	0	1.281	1.275	1.276	1.300	1.345	1.417	0.790	0.794	0.794	0.778	0.752	0.714
5	2.1	1.293	1.278	1.297	1.313	1.359	1.431	0.788	0.798	0.786	0.775	0.750	0.712
10	4.2	1.310	1.297	1.310	1.332	1.381	1.456	0.783	0.791	0.783	0.770	0.742	0.705
20	8.5	1.360	1.318	1.349	1.366	1.403	1.507	0.765	0.790	0.772	0.762	0.742	0.692
33	14.0	1.406	1.364	1.396	1.416	1.469	1.546	0.754	0.777	0.759	0.748	0.721	0.685
50	21.3	1.444	1.437	1.452	1.478	1.537	1.611	0.750	0.754	0.746	0.733	0.705	0.672
Average		1.349	1.328	1.347	1.368	1.416	1.495	0.772	0.784	0.773	0.761	0.735	0.697

of other admixtures, hydrated lime showed a reduction in strength of 0.56 per cent. In using 0.50 per cent in the foregoing discussion a large number of tests from different series using different mixes, consistencies and ages were averaged.

Ironite.—Ground cast iron, weighing 186 lb. per cu. ft., considerably coarser than other admixtures (residue of 45 per cent on 100-mesh sieve), used in quantities up to 10 per cent only, reduced the strength of concrete 0.16 per cent.

Kaolin.—Kaolin reduced the strength 0.41 per cent.

Kieselguhr.—Kieselguhr, from a California deposit, was the lightest of the admixtures used (weight, 13 lb. per cu. ft.). The strength of concrete was reduced 0.48 per cent.

Lava.—Ground lava rock from Twin Falls, Idaho, reduced the strength of concrete 0.40 per cent.

Limestone.—Pulverized limestone from the Chicago district, ground to a residue of 10 per cent on a 200-mesh sieve reduced the strength 0.39 per cent for each 1 per cent of limestone.

Mica.—The material used was a white flake mica ground in a laboratory tube mill. At earlier ages the strength of the concrete was slightly increased with the smaller percentages of

mica. At 28 days and later periods the strength was reduced about 1.1 per cent for each 1 per cent admixture. These tests do not bear out the conclusions based on published reports which show a very great reduction in mortar strength due to mica. Other tests are now under way in which a number of micaceous sands will be used.

Natural Cement.—Natural cement purchased in the Chicago market, was used in both compression and wear tests. (See Tables VIII, XIV and XX.) These tests included mixtures from straight Portland to straight natural cements. While natural cement gave a considerable strength when used alone, it is interesting to note that when mixed with Portland cement it caused a reduction in strength for all percentages and for all consistencies and ages of concrete and gave results comparable in every way with other admixtures. Under the conditions mentioned above, the strength of concrete was reduced 0.38 per cent for each 1 per cent added.

Pitch.—Pitch was pulverized to a very fine powder; the fineness could not be determined by ordinary sieving methods. So far as the writer is aware, no one has advocated the use of this material in concrete; it was included in this investigation in order to study the effect of a powder of unusual origin on the strength of concrete. The strength was reduced 1.5 per cent for each 1 per cent of pitch.

Sand.—Clean silica drift sand from the Chicago district, ground to the fineness of Portland cement, reduced the strength of concrete 0.37 per cent for each 1 per cent sand.

Slag.—Granulated blast furnace slag ground in the laboratory to the fineness of Portland cement. The results of tests with slag differed essentially from all other admixtures in that the strength of concrete was slightly *increased* for all quantities up to 50 per cent of the volume of the cement which was the highest value used. This statement applies to mixes from 1 : 9 to 1 : 4, to different consistencies and ages. The 1 : 3 mix showed a slight loss in strength with the addition of slag. For the conditions discussed for other admixtures the slag increased the strength 0.12 per cent for each 1 per cent added. A similar relation has been pointed out by other writers both in this country and Europe. This result has been explained as due to

TABLE XXIII.—EFFECT OF HYDRATED LIME ON THE YIELD AND DENSITY OF CONCRETE.

6 by 12-in. cylinders.

Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in., fineness modulus, 5.75.

Admixture added to materials in batch; expressed as percentage of *volume* of cement.

Yield is the volume of concrete produced by one volume of mixed aggregate.

Density is the total solid material in the mass.

Yield and density were calculated from weights determined immediately on removal of the cylinders from the forms.

Each value is the average of five tests made on different days.

See Table XXII for other data on yield and density of concrete.

Hydrated Lime, per cent of cement.		For Different Sizes of Aggregate.													
		Yield of Concrete.							Density of Concrete.						
By Volume.	By Weight.	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to ⅜ in.	0 to ¾ in.	0 to 1½ in.	0 to No. 28	0 to No. 14	0 to No. 8	0 to No. 4	0 to ⅜ in.	0 to ¾ in.	0 to 1½ in.
1 : 5 CONCRETE. RELATIVE CONSISTENCY, 1.10. SERIES 130.															
0	0	1.151	1.140	.....	1.077	1.076	1.060	1.032	0.633	0.649	.....	0.716	0.762	0.806	0.839
5	2.1	1.157	1.127	.....	1.091	1.064	1.050	1.043	0.633	0.661	.....	0.709	0.772	0.817	0.833
10	4.2	1.162	1.133	.....	1.104	1.070	1.055	1.048	0.632	0.658	.....	0.703	0.770	0.816	0.833
20	8.5	1.156	1.126	.....	1.106	1.079	1.077	1.056	0.641	0.669	.....	0.708	0.769	0.805	0.833
33	14.0	1.157	1.122	.....	1.101	1.089	1.083	1.075	0.647	0.677	.....	0.717	0.769	0.807	0.824
50	21.3	1.168	1.148	.....	1.110	1.099	1.143	1.096	0.649	0.671	.....	0.720	0.772	0.773	0.818
Average		1.158	1.132	.....	1.098	1.080	1.078	1.058	0.639	0.664	.....	0.712	0.769	0.804	0.830
1 : 4 CONCRETE. RELATIVE CONSISTENCY, 1.10. SERIES 130.															
0	0	1.136	1.159	.....	1.121	1.106	1.100	1.077	0.663	0.660	.....	0.709	0.762	0.799	0.828
5	2.1	1.168	1.147	.....	1.111	1.105	1.091	1.082	0.648	0.671	.....	0.719	0.766	0.809	0.827
10	4.2	1.166	1.154	.....	1.118	1.102	1.097	1.089	0.652	0.668	.....	0.717	0.771	0.807	0.825
20	8.5	1.180	1.167	.....	1.130	1.123	1.116	1.107	0.649	0.668	.....	0.716	0.762	0.800	0.818
33	14.0	1.196	1.173	.....	1.146	1.137	1.137	1.129	0.650	0.672	.....	0.715	0.762	0.795	0.810
50	21.3	1.224	1.196	.....	1.164	1.157	1.163	1.163	0.644	0.670	.....	0.713	0.760	0.786	0.796
Average		1.178	1.166	.....	1.132	1.122	1.117	1.108	0.651	0.668	.....	0.715	0.764	0.799	0.817
1 : 4 CONCRETE. RELATIVE CONSISTENCY, 1.00. SERIES 114.															
0	0	.....	1.116	1.110	1.096	1.065	1.042	1.050	.....	0.672	0.691	0.723	0.794	0.828	0.842
5	2.2	.....	1.117	1.112	1.100	1.065	1.048	1.057	.....	0.675	0.693	0.724	0.798	0.828	0.841
10	4.5	.....	1.120	1.113	1.102	1.071	1.060	1.062	.....	0.676	0.695	0.725	0.796	0.821	0.838
20	8.9	.....	1.132	1.127	1.103	1.093	1.073	1.080	.....	0.674	0.693	0.730	0.786	0.818	0.831
33	14.7	.....	1.144	1.142	1.122	1.112	1.093	1.098	.....	0.676	0.691	0.726	0.780	0.811	0.828
50	22.3	.....	1.170	1.162	1.142	1.131	1.130	1.123	.....	0.671	0.689	0.724	0.778	0.795	0.820
Average		.....	1.133	1.128	1.110	1.089	1.074	1.078	.....	0.674	0.692	0.725	0.789	0.817	0.833

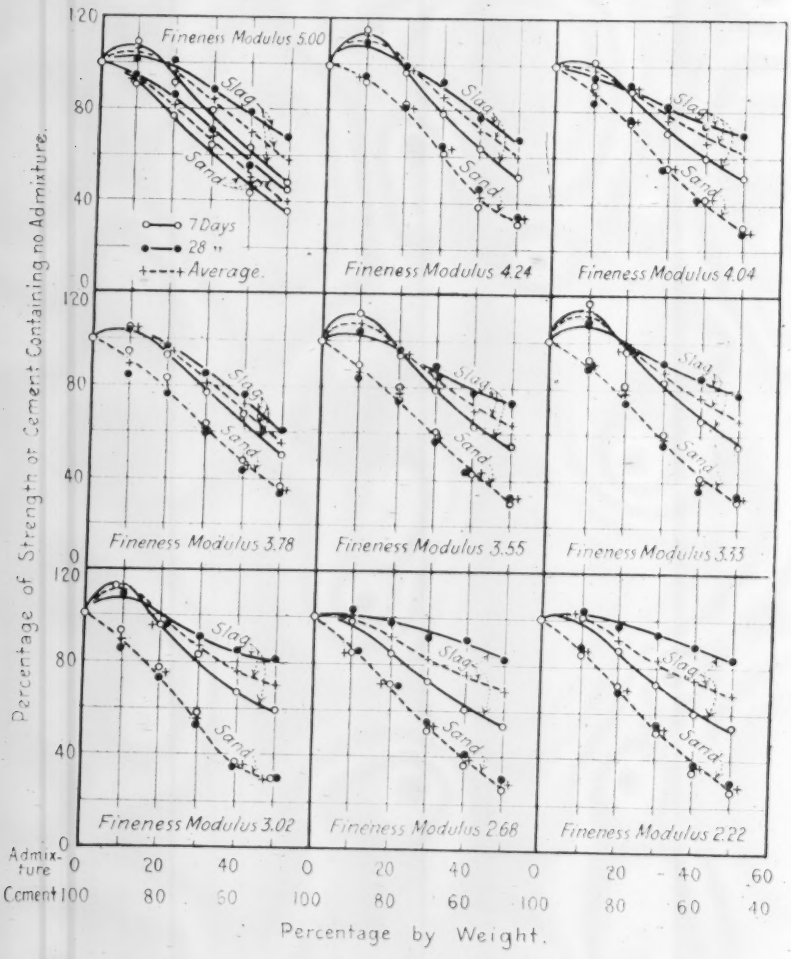


FIG. 12.—Relative Strengths of Sand and Slag Cements.

(Series 59.)

Values expressed as percentages of strength of mortar or concrete using Portland cement without admixture.

Sand or slag was added to the cement prior to final grinding.

For mortar strength and miscellaneous tests of sand and slag cements, see Table I.

For grading of aggregates see Table II. The fineness modulus of the aggregate was varied by causing the grading to conform to certain predetermined smooth sieve analysis curves.

Specimens stored in water; tested wet.

Each value is the average of 6 to 8 tests made on 3 or 4 different days.

Further details of these tests are not reported.

Compare Figs. 6 and 11.

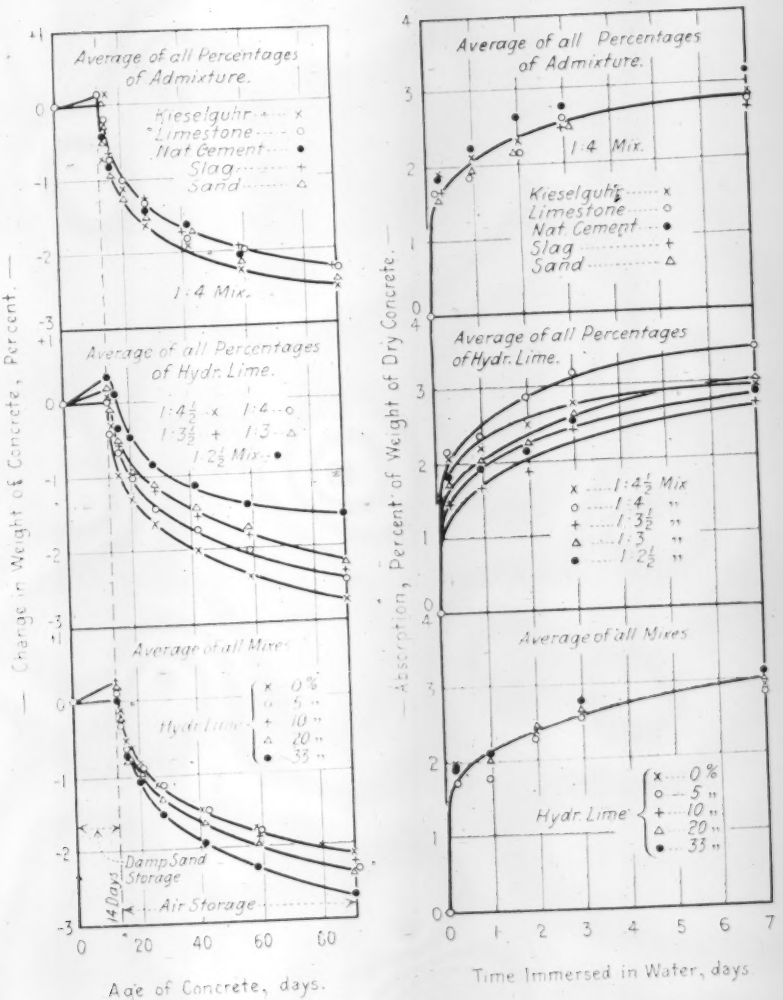


FIG. 13.—Effect of Powdered Admixtures in Concrete on the Evaporation and Absorption of Water.

(Series 130.)

Tests made on 8 by 8 by 8-in. wear blocks; evaporation tests were made during the period of air storage in the laboratory, following 14 days in damp sand. Absorption tests were made on the same blocks, subsequent to the wear test, at the age of about 6 months.

Each value for evaporation is the average of 75 tests made in sets of 5 on 3 different days.

Each value for absorption is the average of 10 to 25 tests.

See Tables XX and XXI for results of wear tests.

chemical reactions between the slag and certain compounds in the cement. The principal constituents of this slag were: SiO_2, 34.8 per cent; CaO, 42.6 per cent; Al_2O_3, 15.0 per cent; Fe_2O_3, 3.7 per cent.

Tufa.—Tufa, a light, loosely-formed natural rock from Mount Angel, Ore., ground with difficulty, reduced the strength of concrete 0.51 per cent.

Whiting.—Commercial grade of whiting, reduced the strength of concrete 0.24 per cent.

Yellow Ochre.—Yellow ochre from Cartersville, Ga., reduced the strength of concrete 0.68 per cent.

EFFECT OF ADMIXTURES ON THE WEAR OF CONCRETE.

Three different groups of wear tests were carried out; see Tables XI, XX and XXI. All wear tests were made in the Talbot-Jones rattler, using 8 by 8 by 5-in. concrete blocks. The wear blocks were tested at 3 months after 14 days in damp sand, followed by air storage. Wear tests were made with admixtures of hydrated lime, kieselguhr, powdered limestone, slag, sand, and natural cement. This test was of such severity as to produce a wear of 0.4 to 0.5 in.

Slag showed the best results since the wear was no greater with 33 per cent slag than with straight cement; sand gave nearly as good results as slag; the other admixtures may be placed in the following order of merit; hydrated lime, natural cement, limestone and kieselguhr. There seems to be little reason for using these materials in concrete roads and other concrete subjected to wear; it is of interest to know that some of them do little or no harm. The principal danger from the use of admixtures in road concrete is that any excess of mixing water will cause the fine material to be floated to the surface and thus give concrete of inferior wearing resistance. The same statement applied to silt in sands and to crusher dust. Silt may contain organic impurities which materially reduce the strength of concrete.[1]

[1] See "Effect of Tannic Acid on the Strength of Concrete," by Duff A. Abrams, Appendix II, Report of Committee C-9 on Concrete and Concrete Aggregates, Part I, p. 309.

SAND AND SLAG CEMENTS.[1]

Two of the earlier investigations included tension and compression tests of mortar and concrete using sand and slag cements. In the preparation of these materials, the sand or slag was added to the cement before final grinding. The tests are summarized in Figs. 11 and 12. Mortar and miscellaneous tests are given in Table I. The slag cements showed more

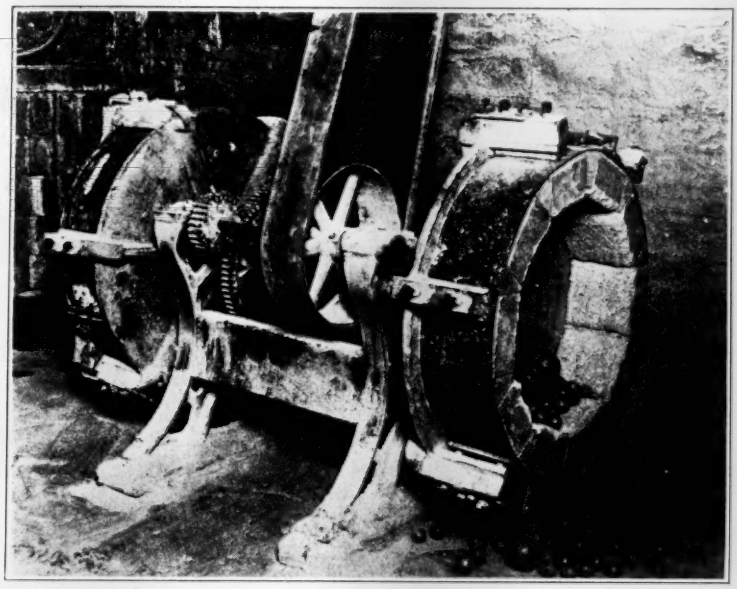


FIG. 14.—Talbot-Jones Rattler for Wear Tests of Concrete.

Wear tests were made on 8 by 8 by 5-in. concrete blocks, after storage for 2 weeks in damp sand and 10 weeks in air.

Test consists of 1800 revolutions of the head at 30 r. p. m., using 200 lb. of cast-iron balls; 10 balls, 3¾ in. in diameter and about 140 balls, 1¾ in. in diameter.

favorable results in all cases than the sand cements; slag up to 10 per cent produced no appreciable reduction in strength of 1 : 2 : 4 concrete; for 50 per cent slag the concrete strength was reduced to 65 per cent of the strength with cement only.

[1] The term "slag cement" is used in this paper to designate a mixture of Portland cement with various percentages of pulverized granulated blast furnace slag. The slag may be simply mixed or ground with the cement; in our case it was mixed. Care should be taken to distinguish between our usage and the same term applied to a product resulting from grinding slag with hydrated lime. Our use of "slag cement" is cognate with "sand cement."

Mortar strengths were less affected than the concrete; the lean briquettes showed a strength with 50 per cent slag of about 95 per cent of cement only. It will be seen that the concrete tests do not bear out the indications of the briquette tests. The compression tests of 1 : 2 mortar, Fig. 11, show essentially the same result as the concrete.

Sand cements give less favorable results than the slag cements. In comparing these tests with the results from other admixtures it should be borne in mind that here cement was replaced by sand or slag. In general the effects of admixtures *ground* with cement are similar to those found with same materials simply mixed. Of course, some consideration must be given to the effect of the finer grinding of the cement in increasing the strength of the concrete.[1] It was impracticable to determine how much the fineness of the cement was changed by the addition of different percentages of sand or slag.

GENERAL DISCUSSION.

The following discussions of a general nature have no direct bearing on the effect of admixtures:

Effect of Quantity of Cement. The wide variation in the mixes used in these tests furnish information on the effect of variations in the quantity of cement. Fig. 8 gives a typical curve for 28-day tests. For the usual mixes (1 : 5 to 1 : 4) the strength increased 1 per cent for each per cent addition of cement. The same value was found in our tests on "Effect of Fineness of Cement" referred to above.

Consistency of Concrete. A typical strength-relative consistency curve is shown in Fig. 8 for 1 : 4 concrete; similar curves may be drawn for other mixes and conditions from data given in the tables. The quantity of water in terms of the water ratio is given in many of the tables.

Fineness Modulus of Aggregate. A typical fineness modulus strength curve is given in Fig. 8 for 1 : 4 mix. The circles and crosses refer to tests made in different groups giving fineness modulus values derived in different ways; see Tables VI and VII. This curve shows the same relation that has been found

[1] See "Effect of Fineness of Cement," by Duff A. Abrams, *Proceedings* Am. Soc. Test. Mats., Vol. XIX, Part II, p. 328 (1919).

in many other investigations carried out in this laboratory; see *Bulletin* 1, referred to above.

Effect of Age of Concrete.—All tests included in this report show that the strength of concrete increased with age so long as the concrete does not dry out. Fig. 8 shows a typical age-strength relation for concrete stored in a damp place. Table IX shows that after concrete dries out (upon exposure to air for 2 to 4 weeks) there is little or no further increase in strength.

Curing Condition of Concrete.—Table IX shows the importance of curing concrete under favorable conditions.

CONCLUSIONS.

The principal conclusions from these investigations are as follows:

1. In general the addition of powdered materials reduced the strength of concrete approximately in proportion to the quantity of admixture. Some exceptions are noted below.

2. In usual concrete mixtures, each 1 per cent of hydrated lime (in terms of the *volume* of cement) reduced the compressive strength 0.5 per cent; 1 per cent by *weight* of cement reduced the strength 1.2 per cent. The reduction in strength caused by *replacing* cement with an equal volume of hydrated lime was about $1\frac{3}{4}$ times that caused by adding hydrated lime.

3. High calcium and high magnesium limes produced the same effect.

4. The addition of 1 per cent of the following powdered admixtures in terms of the volume of cement *reduced* the strength of 1 : 4 concrete at 28 days by the following percentages: Brick, 0.08; clay, 0.22; whiting, 0.24; sand, 0.37; natural cement, 0.38; limestone, 0.39; lava, 0.40; fluorspar, 0.43; kaolin, 0.47; kieselguhr, 0.48; tufa, 0.51; hydrated lime, 0.56; ironite, 0.60; yellow ochre, 0.68; mica, 1.10; pitch, 1.50; gypsum, 4.00. For the same conditions the addition of 1 per cent of cement *increased* the strength of concrete about 1 per cent.

5. Pulverized slag up to 50 per cent of volume of cement gave a slight increase in strength of concrete (about 0.12 on the basis used above).

6. Rich concrete mixes showed a greater loss in strength

due to powdered admixtures than the leaner ones. Lean mixes (1 : 9 to 1 : 6) and in those with aggregates graded too coarse for the quantity of cement used, the strength was little affected or was slightly increased by admixtures up to 50 per cent.

7. The wetter mixes showed a greater loss in strength than the dry, due to the addition of hydrated lime.

8. The effect of admixtures was in general independent of the age of the concrete.

9. Sand and slag cements gave results comparable to those from powdered materials simply mixed in the concrete.

10. Hydrated lime and other powdered admixtures used in these tests slightly increased the workability of the leaner mixes (1 : 9 and 1 : 6) as measured by the slump test. Ordinary mixes (1 : 5 and 1 : 4) were little affected; richer mixes (1 : 3 and 1 : 2) were made less plastic.

11. The wear of concrete was not sensibly increased by hydrated lime or other admixtures up to 20 per cent of the volume of cement.

12. The bond resistance was affected in the same manner as the strength by the presence of hydrated lime.

13. Hydrated lime had little effect on the absorption of dry concrete, increased the evaporation of water from wet concrete and produced no beneficial effect on the strength of concrete stored in air.

14. Powdered admixtures increased the yield of concrete. For hydrated lime in the usual concrete mixtures the increase in volume of the concrete (yield) was about 60 per cent of the loose volume of lime added.

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DISCUSSION.

Mr. Boyd.

MR. D. K. BOYD.—As Chairman of Committee C-7, I have been greatly interested in this exhaustive paper of Mr. Abrams. To me, however, the paper would seem to have the effect of perhaps leading to some erroneous conclusions if applied practically, due to the fact that the results are those of tests made under a wide range of conditions where it is neither recommended nor even suggested, as I know it, that hydrated lime should be used. I hope therefore that some of those present who are familiar with all of the properties of lime will enliven the occasion and enlighten us more by discussing the subject.

Mr. Upham.

MR. C. M. UPHAM.—I am sorry that I did not have an opportunity to read the paper until to-day, and then I had to read it in a more or less casual way. As it is a paper that covers such a wide field and includes so many tests, of course it is impossible to discuss it at length or with any great degree of accuracy. However, I think it is a wonderful bit of information and should be received with a great deal of confidence. I could not, however, at first reconcile some of the conclusions that were drawn with some of the experiments that we have been carrying on. In other words, when we made, as near as we could, direct tests on specimens taken from a concrete mixer in the field, we secured results that would advocate, to a certain degree, the use of hydrated lime within limits. After going into the paper a little more thoroughly and studying it, I see that practically all our tests coincide very closely with the results given in this paper. However, I think that the conclusions, as they are drawn, might mislead one who is just hastily reading the paper or one that has not given any great amount of time to the study of the use of hydrated lime.

I do not know that I need take up any of the details, but the one point that I wish to bring out is that the paper covers a very wide range in the tests; in other words, the mixtures of concrete used, I think, are from 1:2 to 1:9. The amounts of hydrated lime used in the tests covered by the paper I think

Mr. Upham.

are from zero to 50 per cent. The conclusions drawn are from this wide range of tests. As a matter of fact, in practical work, the concrete that is mostly used is neither a 1:2 nor 1:9, but it is a narrow range in between these proportions. Our popular proportion in road work is 1:2:4 or 1:1½:3, and the amount of lime used is neither zero nor 50 per cent, but a narrow range in between these, a range that approximates 10 per cent by volume. The conclusions in the paper are undoubtedly drawn from taking all the mixtures of concrete from 1:2 to 1:9 and from the use of hydrated lime from zero to 50 per cent.

Now I would just draw your attention to Table V and ask you to look in the fourth column under the 1:5 mixes and under the compressive strength for different mixes in pounds per square inch. You will note that in the three days tests, where there is used a 5 per cent addition of lime, there is an increase in strength. In the seven days test, where there is a 5, 10, and 20 per cent addition of lime, there is an increase of strength; in the three months there is an increase for the 5 per cent. Now those figures represent the nearest figures to our popular proportions of concrete, and represent that little division of proportions which we use mostly, and show that hydrated lime is beneficial to the compressive strength of concrete. The conclusions, as I understand them from the paper, are drawn over the entire range of experiments and take into consideration the practical as well as the impractical proportions.

Just one other point: In Table VI, in the 1:5 mix, under the compressive strength in pounds per square inch for the age of 28 days, is shown that with 10, 20, 33, and 50 per cent of hydrate there is an increase of strength. In the same column where the fineness modulus is 5, there is also an increase in strength where 10 per cent of lime is used. That again is about the proportion and the amount of lime that is generally used in the greater part of concrete work.

The farther away from laboratory conditions we get, the more good effect hydrated lime has on concrete. Under purely laboratory conditions hydrated lime may not have such good effect; but in the field, where it is almost impossible to duplicate laboratory conditions, we have found that hydrated lime assists in increasing the strength, and I think the facts in Table

Mr. Upham. IX will bear me out in the use of 10 per cent of hydrated lime (which again is the percentage we have always advocated in the use of concrete). The field condition, in most cases, would not be a damp sand storage. The concrete might be wet for the first day before it drys out; then it quite often happens that the concrete is not wet again except when it rains. The worst condition is to have the concrete deposited and then not have it wet again until it attains its final strength; Table IX again bears out this statement when using 10 per cent of hydrated lime. If you will note, when stored one day in the damp sand, and then in dry air storage from 7 days up to one year, there is a continued increase in strength; in other words, it is 1850 lb. where it is one day in damp sand and 6 days in air, and then when it is 14 days in air, it is 2260 lb.; at the end of 28 days, it is 2770; at the end of 3 months, it is 3120, and at the end of one year, it is 3190 lb. So that again substantiates that where hydrated lime is used within our popular proportions, as you might call it, there is an advantage on the strength of the concrete.

I have a curve marked in Fig. 2 that represents a point of advantage better than anything we have said. Take the 1 year test, of the 1:4 mix; you will note, the curve starts at about 5000; when about 5 per cent by volume of the hydrated lime is used, there is an increase in strength; where 10 per cent is used, I think it is about the same, and then it decreases with larger amounts of lime. As I understand the lime recommendation, the maximum amount advocated is 10 per cent by volume. You can see that these small quantities show an increase in strength, while larger quantities taken over a wide range, may show a decrease.

Mr. Talbot. MR. A. N. TALBOT.—I should like to ask a question concerning the effect of the addition of powdered material and the quantity of water required to produce a given consistency; or, to put it the other way, the consistency which is obtained with the same amount of water in both cases. Is there anything in the tests to determine, in a measurable way, whether there is a difference in the consistency produced when a given amount of water is used both with and without the addition of the powdered material; or, if the same amount of water is used, is there a difference in the consistency?

MR. G. W. HUTCHINSON.—Relative to evaporation: As I understand the paper, the results were obtained after 14 days' storage in damp sand, and showed an increase where hydrated lime was used. As Mr. Upham stated, it is found impossible under some circumstances to keep the road wet at all times; so that it was desired to find how much of the moisture left the mass during the early period. We undertook tests along the same line as Mr. Abrams, only instead of starting at the 14-day period, we started immediately after the specimens were molded and the percentage of lime used was from zero to 10 per cent by weight. The conclusions we came to were that the slab containing lime lost moisture at a slower rate than those that did not have lime in them, and that the amount of moisture lost was in inverse ratio to the amount of lime in the slab. These results were obtained up to the 14-day period only, as from that time until the 22-day period, the loss was constant as well as very small for all percentages. Mr. Hutchinson.

In the field, we have two experimental slabs under observation. The first was laid containing no lime and the second containing 5 per cent of hydrated lime. The measurement of these slabs, which were taken over a period of about two and one-half years, have shown that both the initial contraction and the ultimate movement of the lime slab is only about 50 per cent of the one without lime, and while we are not in position to state definitely whether that is any advantage or not, the less the slab movement, the safer we feel. From these results, I feel that lime is a large factor in retaining moisture in the slab where it is not always possible to keep the roads wet for the first 14 days.

MR. HARRY GARDNER.—I have had occasion to make a few tests of the effect of lime on concrete, and I think I can confirm what both Mr. Upham and Mr. Abrams have said. I had occasion to use lime mixtures at one time, and made a small series of tests. I found that in the richer mixtures, hydrate of lime, if anything, reduced the strength, and in the leaner mixtures, it increased it considerably, confirming what Mr. Upham has said about 10 per cent. I found also, answering Mr. Talbot, that the effect on consistency was probably proportional to the percentage of hydrated lime which was mixed in the cement. Mr. Gardner.

Mr. Gardner. In addition to those strength tests, I made some on permeability, and I should like to ask Mr. Abrams if he has made any of those tests in connection with his strength test? If so, I should like to know what his results are, because hydrated lime is used and has been used considerably in places out through the West. In fact, the reason that I made those tests was to find out whether hydrated lime was practicable or not for waterproofing purposes in concrete tanks. I wonder if Mr. Abrams has done any work of that kind?

A Member. A MEMBER.—I would like to ask the gentleman who advocates the use of hydrated lime in roads—I believe he stated that he finds less contraction and expansion in a road in which he uses hydrated lime—if he find less cracks in the road where he has used hydrated lime than in the roads in which this material is not used?

Mr. Hutchinson. MR. G. W. HUTCHINSON.—We have cracks, but since we started using hydrated lime on the roads, the roads where we did not use it are cracked more than those where we have used it; but as we have also improved on our construction methods, to say the lime was accountable for it might be saying too much for it, so I would not state that the use of lime is alone responsible for fewer cracks.

Mr. Upham. MR. C. M. UPHAM.—Mr. Hutchinson did not discuss one experiment which was tried out in that very connection which may answer the question. When we first started the use of hydrated lime in road work, we tried various percentages every other day; I think we tried zero, 5 and 10 per cent by volume. We put no joints in the road, and consequently the slabs were of various lengths; they varied possibly from 25 ft. up to 200 or 300 or 350 ft. The first study of that condition, which took place about one year after the slabs were made, showed that there were a greater number of slabs containing 5 per cent of lime that had not cracked than there were of the zero percentage, and there was a still smaller percentage of slabs not cracked where 10 per cent of lime was used than where 5 per cent was used. That was the only time that a survey was made, and it has been now three or four years since that survey, so I can not give you any recent data. However, that prevailed at that time.

MR. L. H. HART (*by letter*).—Many of the points in Mr. Abrams' paper deserve further emphasis to bring out their application within practical limits, since there is no information in the conclusions as to the effect of *usual* amounts of lime. In the following discussion certain of these conclusions are quoted from the paper and commented upon with reference only to hydrated lime. **Mr. Hart.**

"1. In general the addition of powdered materials reduced the strength of concrete approximately in proportion to the quantity of admixture. Some exceptions are noted below."

All percentages of hydrated lime up to 50 per cent are averaged together, and the assumption is made that "the relation is a straight line"; but much of the data shows the essential fact that small amounts of admixtures are beneficial even though larger amounts reduce strength. This tendency is so apparent in the plotted points that further study of usual amounts of lime would seem advisable. Of the curves and tables relative to compressive strength practically half (46 per cent) contain points and figures *higher* than the corresponding plain specimens. These are mostly within the following limits, which represent the maximum amounts used in actual practice:

1:3:6	Concrete	12	lb.	hydrated	lime	per	sack	of	cement	(=30% by volume)
1:2½:5	"	10	"	"	"	"	"	"	"	(=25% " ")
1:2:4	"	8	"	"	"	"	"	"	"	(=20% " ")
1:1½:3	"	5	"	"	"	"	"	"	"	(=12½%" ")

(For waterproofing purposes, 15, 12, 10, and 7 lb. respectively.)

Forty-two per cent of all the specimens were of 1 : 1½ : 3 mix.

"2. In usual mixtures, each 1 per cent of hydrated lime (in terms of the volume of cement) reduced the strength of concrete 0.5 per cent . . ." By "usual concrete mixtures" are meant 1 : 4 (equivalent of ordinary 1 : 1½ : 3) and 1 : 5 (1 : 2 : 4) mixes; the 1 : 2½ : 5 which is still so commonly used, and in which the beneficial effects of lime are much more marked is ignored. Those who examine the curves and tables will agree there is a field wherein lime adds to the strength of concrete, and a much larger one still where slight losses in strength in the laboratory are more than compensated by the beneficial effects. The properties attributed to lime in concrete, which account for its rapid adoption in recent years, are not added strength (as

Mr. Hart. suggested here), but reduced segregation of aggregates; better flow in chutes, around reinforcement, and under the trowel; freedom from structural defects, such as honeycombing; smoother, more uniform surfaces; and watertightness.

The assumption is evident throughout that the moment we begin adding lime we begin reducing strength: that is, "the relation is a straight line." The numerical results and plotted points however, do not support this contention, as can be seen by drawing the curves according to any of the mathematical methods, rather than "by eye" as has been done. Some examples are: Fig. 2, where one finds only two decreases, and eleven cases where strength is increased within the above limits; Table VII, where there are only three groups of tests in eighteen in which lime does not increase the strength; Fig. 1, where 75 per cent of the curves show no measurable decrease within these limits; and especially the summary in the lower righthand corner of Fig. 1 where all the "straight line curves" pass below the 5 and 10 per cent points and no decreases are shown for these amounts of lime.

"4. The addition of 1 per cent of the following powdered admixtures in terms of the volume of cement reduced the strength of 1 : 4 concrete at 28 days by the following percentages: . . . hydrated lime, 0.56 . . ." This conclusion states the effect of "the addition of 1 per cent" of lime, but in no test specimen has 1 per cent been added; never less than 5 per cent, and in some cases the minimum is 10 per cent. Furthermore, as pointed out under No. 1, all percentages have been averaged together by the "straight line" method, eliminating the effect of small amounts and utilizing points up to 50 per cent in establishing the straight line theory. This conclusion refers only to 1 : $1\frac{1}{2}$: 3 concrete at 28 days, the age which in these tests, for some reason, is the least favorable one for lime specimens.

"6. Rich concrete mixes showed a greater loss in strength due to powdered admixtures than the leaner ones. Lean mixes (1 : 9 to 1 : 6) and in those with aggregates graded too coarse for the quantity of cement used, the strength was little affected or was slightly increased by admixtures up to 50 per cent." The conditions under which these increases occur represent a large part of the annual yardage placed.

"7. The wetter mixes showed a greater loss in strength than the dry, due to the addition of hydrated lime." The point should be brought out here that as lime increases plasticity, batches need not be so wet and at the same time lime does not evaporate leaving injurious pores behind, as water does when used to increase plasticity. Mr. Hart.

In Fig. 7, by the addition of 50 per cent of lime (but no increase in water), increases in strength up to 75 per cent are shown. This is due only *in part* to the reduced wetness, lime absorbing some of the moisture, and at the same time increasing plasticity so that drier mixes can be used.

"10. Hydrated lime and other powdered admixtures used in these tests slightly increased the workability of the leaner mixes (1 : 9 and 1 : 6) as measured by the slump test. Ordinary mixes (1 : 5 and 1 : 4) were little affected; richer mixes (1 : 3 and 1 : 2) were made less plastic."

The reader is asked to compare the average slump in each column, with the corresponding slump without lime. Only eleven of the thirty-six averages, for all mixes and all amounts of lime, are less with lime than without (Table XVI). The average increases with lime are: 1 : 6, 31 per cent; 1 : 5, 112 per cent; 1 : 4, 37 per cent; 1 : 3, 19 per cent; 1 : 2, 12 per cent. In 1 : 2 mortar, 5 per cent lime shows 26 per cent increase, and 10 per cent of lime; 34 per cent increase (average of all consistencies). The average of the four richer mixes shows a consistent gain up to 33 per cent lime, contradicting the statement that "for the richer mixes the slump was decreased."

"11. The wear of concrete was not sensibly increased by hydrated lime or other admixtures up to 20 per cent of the volume of cement." Resistance to wear is investigated in Table XI. Only rich mixes were studied. Of ten cases, seven show an average of 8 per cent less wear with 10 per cent of lime than without, and the eighth case shows less wear with 33 per cent of lime; the average of all figures using 10 per cent hydrated lime (12.5 per cent is the advocated percentage for 1 : 4 concrete) shows a decrease in the wear of 2.7 per cent. Tables XX and XXI, from another series, confirm the above. Four cases out of five show less wear with 5 per cent of lime.

"12. The bond resistance was affected in the same manner

Mr. Hart. as the strength by the presence of hydrated lime." Since with 10 per cent of lime, only two of the four ages studied show decreased bond, it is hard to see how any conclusion can be drawn. Here hydrated lime was substituted for, rather than added to the cement, but this is now known to be poor practice and might change the whole result.

It is felt that these tests indicate that lime in concrete, in the usual amounts, does not reduce strength, but aids materially in increasing the plasticity, resistance to wear, volume, and freedom from voids. As lime is not hydraulic, damp sand storage is not a favorable condition, but 88 per cent of the specimens were stored damp until tested. Had the conditions been more like those of actual field practice, lime would have made even a more favorable showing. In general, however, the tests were well planned. They have a wider scope than ever before attempted, and show more refinement of methods and more care to eliminate errors. While there are many erratic figures, the series compares well in this respect. All that can be asked is suitable emphasis on the significant points in the results.

Mr. Abrams. MR. D. A. ABRAMS.—In answer to Prof. Talbot's question. In carrying out the last investigation (Series 130) we paid particular attention to the workability of the concrete. It is true that we have not as yet developed a satisfactory method for determining workability. The method we used consisted of molding a 6 by 12-in. cylinder, slipping off the metal form immediately and noting the settlement of the fresh concrete. The slumps for a portion of our tests are given in Table XVI. Those tests and similar ones form the basis for the conclusion stated, that for ordinary mixtures the presence of hydrated lime had no particular effect on the workability, and in the case of richer mixtures, it seemed to make the concrete less workable; in the case of the leaner ones, a little more so.

The additional quantity of water made necessary by the admixture is directly proportional to the normal consistency of the admixture. We made a normal consistency test of each admixture in the same way as in testing cement. This method had been tried in the earlier investigations, and was found reliable. The normal consistencies of the admixtures used are given in Table III. The values varied widely. Kieselguhr required

water equal to 250 per cent of its weight to produce a normal consistency. The lowest value was 8.4 per cent for ironite. The normal consistency of the hydrated lime was about 60 per cent. If we put another material in concrete we must add a quantity of water which is proportional to the quantity of material added, and its normal consistency. Mr. Abrams.

It was a great surprise to the writer that a number of the men who have discussed our report commented somewhat adversely on the wide range of the tests. Many years' experience in testing concrete has shown that it is necessary to cover a wide range in order to determine the underlying principles. A large portion of the concrete tests reported in the literature are almost worthless because they do not cover a sufficient range to give conclusive values. Instead of considering the wide range of the tests a weakness, I believe that it is just that feature to which the report owes its principal value. If we restrict our tests to a narrow range of hydrated lime, consistency, or cement content, we cannot discover underlying relations. A great many engineers have been inadvertently misled by attempting to draw conclusions from a narrow range of tests. That, I think, is sufficient justification for the wide range covered by our tests.

There is no reason why undue weight should be given to the higher percentages of hydrated lime, if one is not interested in those values. The data are there, but attention can be concentrated on the smaller percentages if you prefer. Whether or not the 50 per cent values are considered, has little or no influence on the conclusions.

Mr. Upham called attention to certain figures and seems to find inconsistencies between the diagrams and the conclusions. Reference to the diagrams or the tables will show that the values pointed out are exceptions. Naturally, in testing a material like concrete and plotting the values on a diagram, there will be a slight scattering of the points; in other words, slight variations in the tests will carry one point above the line and another below. A few instances of that kind will be found, but these cannot be taken to invalidate the conclusions based on the unmistakable tendency shown by the vast majority of the tests.

It is well known that concrete tests cannot be made with the precision of length or weight determinations, in which values can be measured accurately to 4 or 5 significant figures. When

Mr. Abrams. we are studying a variable which produces only a slight effect, it may be expected that minor irregularities will occasionally cover up the effect of the variable, if only a narrow range is considered. In order that the strength of concrete containing 5 per cent of hydrated lime may not sometimes be as high or slightly higher than that without hydrated lime, it would be necessary for all strengths to be accurate within 2 per cent (since each 1 per cent of lime reduced the strength 0.5 per cent). Such accuracy cannot readily be obtained; variations below 5 or 6 per cent represent exceptional work.

Mr. Upham states that these are laboratory tests and that we do not find the same conditions in the field. The only difference between the concrete in the laboratory and in the field is that in handling the concrete as we have done, we know exactly what is in each specimen. Unfortunately in the field that is not true; we do not know just what is in the concrete at this point and what is in the concrete at another point; and as a result tests of specimens made in the field generally show wide variations for the same mix. It is to avoid these wide variations that our tests are made so carefully. We do not mean to say that field work must be carried on with the same precision that the laboratory tests are made, but we are endeavoring here to arrive at fundamentals and we must know just how much cement, aggregate, and water is in each batch. If we do not know this we are wasting time by going through the motion of making tests.

Mr. Upham appears to have confused the effect of age of the concrete with the influence of hydrated lime.

Mr. Hutchinson states that tests made in the field on road work in which the concrete was stored in the air gave results different from those given in our report. Attention should be called to the fact that we stored concrete under exactly the condition he mentions; not only that, but a great many other conditions. That is, the concrete was stored in damp sand for different periods of time, then exposed to dry air. We covered the entire range of conditions that is likely to be encountered in road construction. These tests (Table IX and Fig. 9) failed to reveal any advantage due to hydrated lime, whether the specimens are stored in damp sand or in air or combinations of these methods.

Mr. Abrams.

In answer to Mr. Gardner's question: we did not study the permeability of concrete. We are hoping that conditions at a later time will permit us to make a study of permeability. Having established the general relations so far as strength is concerned, it will be a comparatively simple matter to duplicate certain portions of the tests and secure definite conclusions with reference to other factors.

(*Author's Closure by Letter.*)—In these investigations we were primarily interested in the *general* effect of inert powdered admixtures in concrete. We should not lose sight of the fact that many powdered admixtures other than hydrated lime were used in the tests and are of interest to concrete engineers. The tests show that certain types of admixtures (pulverized granulated blast furnace slag, for example) *are beneficial to concrete strength*, possess all the advantages of hydrated lime and probably can be used at a lower cost.

The following remarks refer specifically to the written comments of Mr. L. H. Hart. The articles are numbered in the same order as the conclusions quoted by Mr. Hart.

1. It should be stated that our Conclusion 1 referred to the general effect of many different types of powdered materials. Hydrated lime behaved no differently from the bulk of other powdered materials used in these tests. The effect of hydrated lime was studied by platting the strengths against the percentages of hydrated lime, drawing a smooth curve through these points. In general, curves drawn in this way closely approximate straight lines. The average slope of these lines was taken as a measure of the effect of powdered admixtures on the concrete. The fact that some of the curves and tables contained values with small percentages of hydrated lime which are higher than those without hydrated lime, has no significance unless we inquire into the cause of the effect found in each instance. It is clearly stated in our report that there are fields where hydrated lime increases the strength of concrete. These cases may be classified under the following headings:

1. Lean mixtures,
2. Fine aggregates,
3. Accidental variations in the values which do not affect the general trend of the results.

Mr. Abrams. The effect of hydrated lime under the first two headings is fully discussed in our report. The subject of accidental variations in tests was discussed above.

Mr. Hart objects to our using percentages of hydrated lime higher than those recommended for use in concrete. He does not state on what information these recommendations are based. He also criticises us for not investigating the effect of hydrated lime below 5 per cent; yet the smallest percentage recommended is $12\frac{1}{2}$ per cent.

2. The "by eye" method of drawing curves through plotted points is universally used by engineers; it is quite satisfactory and surprisingly accurate. The nature of the mathematical methods which Mr. Hart has in mind is not divulged. It was not considered necessary to go into an elementary discussion of curve tracing. The cause for minor discrepancies in concrete tests should be apparent to any engineer conversant with this subject.

It is not clear why Mr. Hart has placed particular emphasis on Fig. 2, when a number of these curves are derived from tests made on lean mixtures which, as pointed out in our report, show an increase in strength with hydrated lime. I am at a loss to understand how anyone can interpret Fig. 1 as showing an increase in strength of concrete due to the presence of hydrated lime.

4. The absurdity of studying the effect of hydrated lime by adding 1 per cent of this material to concrete must be apparent to anyone who has had any experience in concrete tests, due to the slight effect of such a small percentage. The absurdity should be all the more apparent to one who has our report before him, since it is there shown that 1 per cent by volume of hydrated lime reduced the strength of ordinary concrete mixtures about 0.5 per cent.

7. The comments made by Mr. Hart with reference to our Conclusion 7 are not borne out by the tests. In order that concrete containing hydrated lime may be plastic, a quantity of water must be added sufficiently to produce a plasticity in the lime which approximates that of the concrete. This has been discussed above. The mere reiteration of the statement "as lime increases plasticity, batches need not be so wet" does not change the observed facts.

Mr. Abrams.

Mr. Hart has misinterpreted Fig. 7, in spite of the explanatory notes which accompany that figure. It is stated in our report that the values in this table do not show directly the effect of hydrated lime on the strength of concrete. We went so far as to give an example illustrating this very point. This diagram shows the fundamental relation between the strength of concrete and the water-ratio. While it is true that for the same water-ratio the strength of concrete with 50 per cent of hydrated lime is higher than that without hydrated lime, we must not lose sight of the fact that we are dealing with concretes of quite different consistencies. If the same quantity of water is used (the same water-ratio) the concrete containing hydrated lime will be drier; allowance must be made for this condition by adding water.

If some of the points on the two curves in Fig. 7 are identified, the absurdity of Mr. Hart's interpretation will become apparent. Consider, for example, the 1 : 4 mixture which in the upper diagram gave a strength of about 3300 lb. per sq. in. with a water-ratio of 0.80; in the lower diagram these points will be found at a strength of about 2400 lb. per sq. in. with a water-ratio of about 1.05. In other words, the strength is reduced 900 lb. per sq. in., due to the presence of the additional water and hydrated lime.

10. We have not claimed that our method of measuring consistency or plasticity of concrete is perfect. In fact it is quite apparent that this is not the case. We are still searching for a satisfactory method of measuring plasticity. Our conclusions are based on a careful study of the values from slump tests, some of which are given in Table XVI. It is pointed out in our report that the slump of leaner mixtures was increased with the addition of hydrated lime.

Mr. Hart's method of calculating the percentages in his discussion of the slump tests is erroneous. The calculation of percentage change in a factor which is limited by definition gives a wrong impression of the relative values. By this method if a cylinder slumped 7 in. and we get "an increase of 112 per cent" we would then calculate a slump of 14 8 in. which is absurd, in view of the fact that a 12-in. cylinder was used.

11. The wear tests in Table XX in which kieselguhr,

Mr. Abrams. powdered limestone, powdered slag, powdered sand and natural cement were used were also considered in formulating our Conclusion 11. The tests in Table XXI covered a wide range of mixtures.

12. With reference to the substitution of hydrated lime for cement, it may be stated that the tests in Table X were made over three years ago, when it was common for the advocates of hydrated lime to recommend the substitution of lime for cement. We recognized that this was a poor practice and it was not followed in later tests.

It should be noted that by covering a wide range of percentages of both cement and admixture we can determine the effect of either method of dealing with the admixture (substitution for cement or addition to the batch) from the same tests.

EFFECT OF RODDING CONCRETE.

By F. E. Giesecke.

Introduction.

Rodding concrete is accomplished by repeatedly pushing a pointed rod into the concrete.

The direct effect of rodding is to expel entrapped air and excess water, and to compact the concrete; the indirect effect is a material increase in the strength of the concrete.

The difference between tamping and rodding concrete is that, in tamping, the upper portion of the concrete is compacted and forms a cushion which protects the lower portion of the concrete and prevents or retards the escape of entrapped air and excess water, whereas, in rodding concrete, a pressure is exerted on the concrete as deep as the rod penetrates, and the escape of entrapped air and excess water is thereby facilitated.

Rodding concrete has an important bearing on the practice as well as on the theory of concrete construction. It is important in actual construction because, when generally applied, a considerable increase in the strength of the concrete or a corresponding saving in cement will be effected. With the ordinary 1:2:4 mix and as much excess water as is generally necessary in reinforced concrete work, thorough rodding will effect an increase in strength of about 100 per cent. The cost of the additional 100 per cent produced by the rodding is very much less than the cost of the original 100 per cent, and the consequent saving is considerable.

Rodding concrete is important in the theory of concrete construction because it has been shown that concrete can be rodded with beneficial effect long after the degree of hardening, known as the initial set, has taken place; this indicates that the hardening of cement paste is primarily due to colloidal action and not to crystallization, and that the fear of injuring concrete by disturbing it during the early portion of the hardening period is not well founded.

In a series of experiments made at the University of Texas in 1917 to determine the physical properties of concrete as deter-

mined by the relative quantity of cement, the results of which were published in *Bulletin No. 1815*, it was shown that excess water greatly reduced the strength of the concrete.

Realizing that in practical operations it is almost absolutely necessary to use enough excess water to make the concrete sufficiently fluid to be handled in wheelbarrows, or tubes, and so that it will flow readily into the forms, and between and around the reinforcing steel, and that such excess water reduces the strength of the concrete materially, the question arose, "What, if anything, can be done to prevent or reduce the injury to the concrete by the excess water?"

To study this question, Mr. G. A. Parkinson, Assistant Testing Engineer, University of Texas, made a number of experiments during the fall and winter of 1917 in which he prepared concrete with a considerable excess of water and, after the concrete had been deposited in the molds, removed the excess water by rodding the concrete. The results of these early tests were so very satisfactory that several series of tests have since been made, of which three will be described.

SERIES OF TESTS TO DETERMINE GENERAL EFFECT OF RODDING.

In June, 1918, eight groups of specimens, designated *A*, *B*, *C*, *D*, *E*, *F*, *G*, and *H*, respectively, were prepared. Each group consisted of six 6 by 12-in. cylinders.

In every case the composition by weight of the concrete was:

Colorado River gravel	P 1¼ in. R ¾ in.	29.7	per cent
" " "	P ¾ in. R ¼ in.	29.5	"
" " sand	P ¼ in. R No. 12	12.0	"
" " "	P No. 12 R No. 50	11.3	"
" " "	P No. 50	3.1	"
Blend of two brands of Texas cement		14.4	"
		100.0	"

This mix corresponds very closely to the ordinary 1:2:4 mix; the resulting concrete contains about 6 sacks of cement per cubic yard of concrete and is exactly the same composition as the 6-sack gravel concrete described in *Bulletin No. 1815*; this permits a comparison of the two sets of results.

The *A* specimens were prepared with water amounting to 6.7 per cent of the total weight of the other materials; they were of a very stiff consistency, were thoroughly tamped while being placed in the molds, and developed an average ultimate compressive strength of 3915 lb. per sq. in. in 28 days and 4559 lb. per sq. in. in 3 months.

All other specimens were prepared with water amounting to 10 per cent of the weight of the other materials or 69.4 per cent of the weight of the cement or about 104.5 per cent of the volume of the cement. The concrete for the specimens was of such a thin consistency that it flowed readily and was difficult to handle with shovels. It contained more water than need ever be used in practice to secure easy handling and a thorough filling of the forms.

Of these seven groups, the concrete for the *B* specimens was deposited in the molds and, as it settled, more was added so that the molds were well filled when the specimens were completed.

The specimens developed an average compressive strength of 1962 lb. per sq. in. in 28 days and 2386 lb. per sq. in. in 3 months.

The *C* specimens were tamped lightly with a wooden tamper. They developed an average compressive strength of 2313 lb. per sq. in. in 28 days and 2343 lb. per sq. in. in 3 months.

The *D* specimens were rodded every 15 or 30 minutes for 4 hours when the concrete had set so firm that the rod would not penetrate more than $2\frac{1}{2}$ in.; these specimens developed an average compressive strength of 4211 lb. per sq. in. in 28 days and 4363 lb. per sq. in. in 3 months.

The *E* specimens were rodded every 10 or 12 minutes for $2\frac{1}{2}$ hours; they developed an average compressive strength of 4188 lb. per sq. in. in 28 days and 4512 lb. per sq. in. in 3 months.

The *F* specimens were rodded every 30 minutes for 7 hours; they developed an average compressive strength of 4644 lb. per sq. in. in 28 days and 4961 lb. per sq. in. in 3 months.

Of the *G* and *H* specimens, one-half were rodded every 30 minutes for $7\frac{1}{2}$ hours and the other half were left untreated like the *B* specimens; the G specimens were stored under usual laboratory conditions and the *H* specimens were left in the molds and exposed to the weather to approximate field conditions.

The rodded *G* specimens developed an average compressive strength of 2770 lb. per sq. in. in 7 days; the untreated *G* specimens a strength of 1522 lb. per sq. in. in 7 days.

The rodded *H* specimens developed an average unit strength of 2611 lb. per sq. in. in 7 days, the untreated *H* specimens a unit strength of 1409 lb. per sq. in. in 7 days.

These results are shown graphically in Fig. 1.

A comparison of the *A* with the *B* specimens shows that the increase of water from 6.7 to 10 per cent decreased the strength of the concrete about 50 per cent.

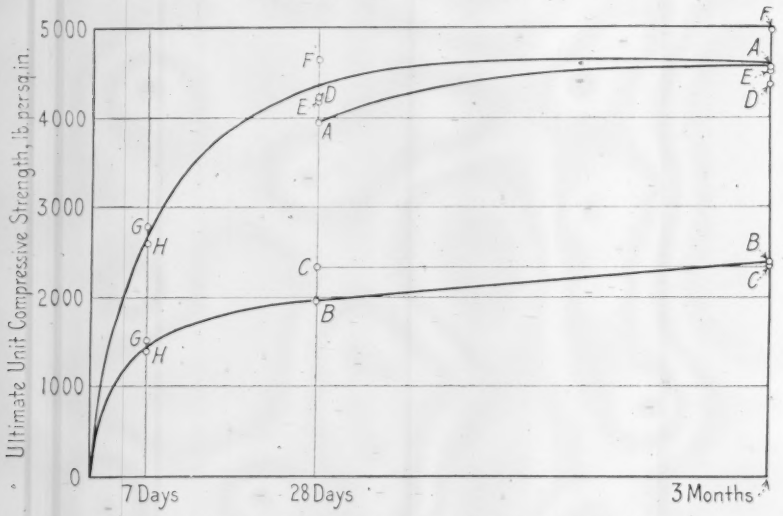


FIG. 1.—Showing the Compressive Strength of Specimens Prepared in June, 1918.

A comparison of the *C* with the *B* specimens shows that the tamping did very little good.

A comparison of the *D*, *E*, and *F* with the *A* specimens shows that the wet concrete thoroughly rodded was a little stronger than the same concrete without excess water.

A comparison of the *D*, *E*, and *F* with the *B* specimens shows that, with this particular type of concrete, the strength of wet concrete can be increased 100 per cent by rodding.

A comparison of the *G* and *H* specimens shows that the effect of rodding is about the same under regular working conditions as under laboratory conditions.

It is important to note that the *D*, *F*, *G*, and *H* specimens were rodded until the concrete was so firm that it was not possible to rod them further; that is, they were rodded for a long period after initial set had taken place, with extremely beneficial results.

In this early work the rodding was not performed as systematically as in the later series of the tests.

A pointed $\frac{5}{8}$-in. round rod was used for the rodding and the rod was pushed into the concrete about fifteen times at each rodding, but no attempt was made to push the rod into the concrete exactly the same number of times at each rodding.

EFFECT OF NUMBER OF AND INTERVAL BETWEEN RODDINGS.

In June, 1919, a series of 54 specimens, 6 by 12 in., were prepared to determine how the effect of rodding varies with the number of roddings and with the interval of time between successive roddings.

The composition by weight of the concrete for these specimens was:

Colorado River gravel			P $1\frac{1}{4}$ in. R $\frac{3}{4}$ in.	29.7	per cent
"	"	"	P $\frac{3}{4}$ in. R $\frac{1}{4}$ in.	29.5	"
"	"	sand	P $\frac{1}{4}$ in. R No. 12	12.0	"
"	"	"	P No. 12 R No. 48	12.2	"
"	"	"	P No. 48	2.2	"
Cement				14.4	"
				100.0	"
Water				10.0	"

The series was divided into three groups of 18 specimens each. In each group, one specimen was not rodded at all; the remaining seventeen were rodded from one to seventeen times, respectively; the only difference between the three groups is in the interval of time between successive roddings which was, respectively, 10, 20, and 30 minutes for the three groups.

The results of the test of this series are shown in Fig. 2, which shows the compressive strength at 28 days. Each value shown in this diagram represents the strength of a single specimen. The diagram is not quite exact with reference to the time element because the first rodding was applied a little earlier

than indicated by the figure. Each rodding consisted of pushing a pointed rod 20 times into the specimen.

The diagram shows that in each of the three groups, an increase in strength of more than 100 per cent was attained in about $2\frac{1}{2}$ hours and that further rodding had no effect on the strength except in the case of the two specimens which were rodded when the concrete was more than $7\frac{1}{2}$ hours old. In these cases the decrease in strength may have been partly due to the fact that the concrete was so stiff that when the rod was drawn out the cavity thereby produced did not close. In testing rodded specimens we found a number of cases in which the con-

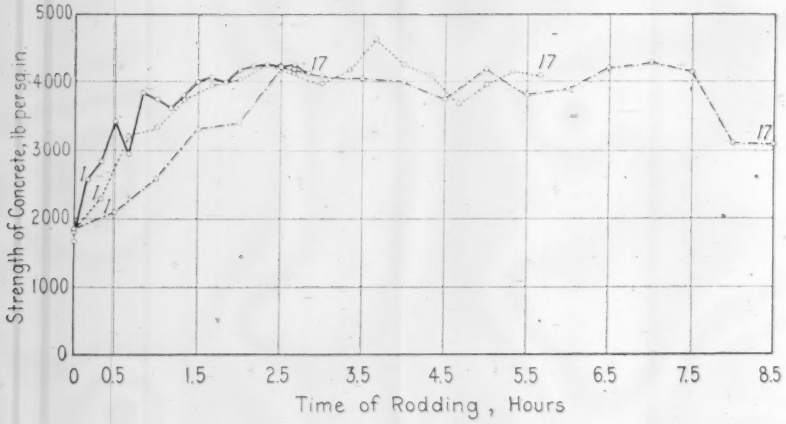


FIG. 2.—Showing the Relation Between the Strength of Concrete and the Time of Rodding.

crete had been rodded so long that the cavity produced by the rod remained in the concrete.

To determine whether the increase in strength of more than 100 per cent shown in Fig. 2 is due to a superior quality of the rodded concrete or to an inferior quality of the unrodded, it will be of interest to compare the strengths of the unrodded specimens with similar strengths secured in the investigations at Lewis Institute made for the Portland Cement Association.

The three unrodded specimens shown in Fig. 2 developed strengths of 1670, 1814, and 1860 lb. per sq. in. respectively, or an average strength of 1781 lb. per sq. in. The average strength of 32 of the specimens shown in Fig. 2, all of which had been

rodded from $1\frac{1}{2}$ to $7\frac{1}{2}$ hours, is 4074 lb. per sq. in. The water-cement ratio was 1.05 and the expected strength, according to the Lewis Institute espression $S = \frac{14000}{7^x}$, is 1814 lb. per sq. in.; in this particular series, the strength of our unrodded specimens was about 2 per cent less, and that of our rodded specimens about 119 per cent more than that calculated by the Lewis Institute formula.

RELATION BETWEEN INCREASE IN STRENGTH DUE TO RODDING AND RELATIVE QUANTITY OF CEMENT.

In January, 1920, a series consisting of forty 6 by 12-in. specimens was prepared to determine how the increase in strength

TABLE I.—GRANULOMETRIC COMPOSITION OF AGGREGATE IN 1920 SERIES.

GROUP E, 4-SACK CONCRETE.			GROUP G, 4-SACK CONCRETE.		
P $1\frac{1}{4}$ in. R $\frac{3}{4}$ in.....	29.50	per cent	P $1\frac{1}{4}$ in. R $\frac{3}{4}$ in.....	29.75	per cent
P $\frac{3}{4}$ in. R $\frac{1}{4}$ in.....	29.50	"	P $\frac{3}{4}$ in. R $\frac{1}{4}$ in.....	29.50	"
P $\frac{1}{4}$ in. R No. 12...	15.95	"	P $\frac{1}{4}$ in. R No. 12...	12.00	"
P No. 12 R No. 22..	6.50	"	P No. 12 R No. 50..	11.25	"
P No. 22.....	8.95	"	P No. 50.....	8.22	"
Cement.....	9.60	"	Cement.....	9.28	"
	100.00	"		100.00	"
Water.....	9.00	"	Water.....	9.00	"

GROUP F, 8-SACK CONCRETE.			GROUP D, 8-SACK CONCRETE.		
P $1\frac{1}{4}$ in. R $\frac{3}{4}$ in.....	29.10	per cent	P $1\frac{1}{4}$ in. R $\frac{3}{4}$ in.....	29.50	per cent
P $\frac{3}{4}$ in. R $\frac{1}{2}$ in.....	28.91	"	P $\frac{3}{4}$ in. R $\frac{1}{4}$ in.....	29.50	"
P $\frac{1}{4}$ in. R No. 12...	11.74	"	P $\frac{1}{4}$ in. R No. 12...	11.05	"
P No. 12 R No. 50..	9.95	"	P No. 12 R No. 22..	4.50	"
P No. 50.....	0.00	"	P No. 22.....	6.20	"
Cement.....	20.30	"	Cement.....	19.25	"
	100.00	"		100.00	"
Water.....	29.30	"	Water.....	29.30	"

of concrete due to rodding varies with the relative quantity of cement in the concrete.

Of the forty specimens, twenty were prepared so as to contain cement at about four sacks per cubic yard of concrete and twenty at about eight sacks per cubic yard.

In each of the two groups, one-half the specimens were rodded seven times with half-hour intervals, each rodding consisting of pushing a pointed rod ten times into the specimen; that is, half as often as in the series shown in Fig. 2, the remaining half were not rodded but the concrete was settled as well as possible by tapping the mold.

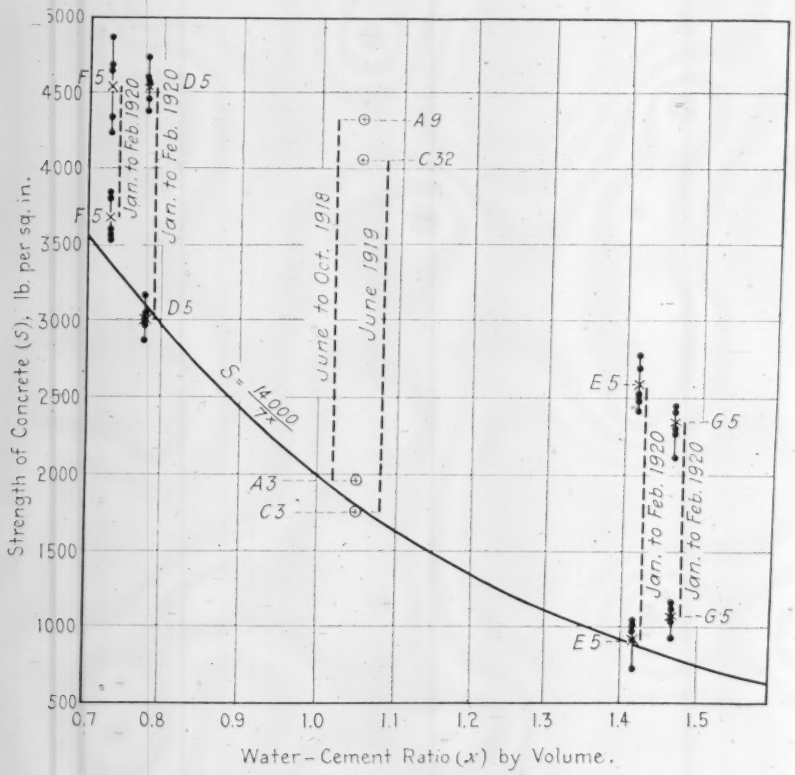


FIG. 3.—Showing the Relation Between the Strength of Concrete and Relative Quantity of Cement for Four, Six and Eight-Sack Concrete, Both Rodded and Unrodded.

Sufficient mixing water was used to secure a flowing consistency in the concrete. All water which came to the surface during the rodding period was poured off.

The two groups were divided into two sub-groups by varying

the granulometric composition of the aggregate as shown in Table I, Colorado River gravel and sand being used in all cases.

The strengths of these specimens at 28 days are shown graphically in Fig. 3 plotted against the Lewis Institute water-cement ratio and in comparison with the Lewis Institute strength formula, $S = \frac{14000}{7^x}$, and also in comparison with the values shown in Figs. 1 and 2, which refer to specimens containing cement at a rate of about six sacks per yard.

The rodded specimens shown in Fig 3 were not rodded according to any uniform method.

In the 1918 series, shown by *A 9*, the specimens were rodded at intervals varying from 10 to 30 minutes until the concrete was so firm that further rodding was impracticable; each rodding consisted of pushing the rod into the concrete about 15 times.

In the 1919 series, for the 32 specimens represented by *C 32*, each rodding consisted of pushing the rod 20 times into the concrete; the specimens received from 6 to 17 roddings, at intervals varying from 10 to 30 minutes.

In the 1920 series, shown by *F 5*, *D 5*, *E 5* and *G 5*, each rodding consisted of pushing the rod ten times into the concrete and each specimen received seven roddings at 30-minute intervals.

Fig. 3 shows:

1. That the strength of good unrodded concrete is given quite accurately by the expression $S = \frac{14000}{7^x}$;

2. That rodded concrete is very much stronger than unrodded concrete;

3. That the relative increase in strength due to rodding is greater for the lean mixes than for the rich;

4. That, for the particular concretes and types of rodding represented in Fig. 3, the increase in strength due to rodding is about 40 per cent for 8-sack, 100 per cent for 6-sack, and 140 per cent for 4-sack concrete.

THE STRENGTH AND MODULUS OF ELASTICITY OF RODDED CONCRETE.

During the summer of 1919 a series of 216 specimens, 6 by 12 in., was prepared to determine how the strength of rodded concrete varies with the relative quantity of cement, with the maximum size of the aggregate, and with the consistency of the mix. The amount of water removed from the concrete by rodding and the modulus of elasticity of the concrete at the age of 3 months were also determined in this investigation.

In this series, three proportions of cement (4-sack, 6-sack, and 8-sack), three maximum sizes of aggregate ($\frac{1}{2}$-in. $1\frac{1}{4}$-in., and $2\frac{1}{2}$-in.), and four consistencies (fairly dry, very wet, and intermediate) were used. The specimens were stored 7 days in water and 84 days in air.

The principal results secured with the $1\frac{1}{4}$-in. maximum size aggregates are shown in Fig. 4; the strength is plotted against the water-cement ratio, the latter being expressed in terms of the quantity of water originally added to the mix and also in terms of the quantity of water remaining in the concrete after the rodding had been completed.

Fig. 4 shows:

1. That the expression $\frac{14000}{7^x}$ does not give the strength of rodded concrete;

2. That the strength of rodded concrete decreases as the quantity of excess mixing water increases;

3. That a very considerable portion of the mixing water is removed from the concrete by rodding, thereby reducing the mobility or flowability of the concrete.

The principal results secured in determining the modulus of elasticity of rodded concrete are shown in Fig. 5; the modulus of elasticity is plotted against the ultimate compressive strength at the corresponding age. Every value shown in this figure is the average of the values of three specimens but every one represents a distinct type of concrete differing from every other type in the consistency of the mix, or in the maximum size of the aggregate, or in the relative quantity of cement. The values of the modulus shown in this figure were taken from those parts

of the stress-deformation diagrams which represent stresses of, approximately, 15 to 40 per cent of the ultimate.

The curve in Fig. 5 shows the value, 66,000 $S^{1/2}$, determined by Mr. Stanton Walker, from a very large number of tests made at Lewis Institute, as the tangent modulus of elasticity of concrete at 25 per cent of its compressive strength.[1] It is evident from Fig. 5 that the modulus of elasticity of rodded concrete is

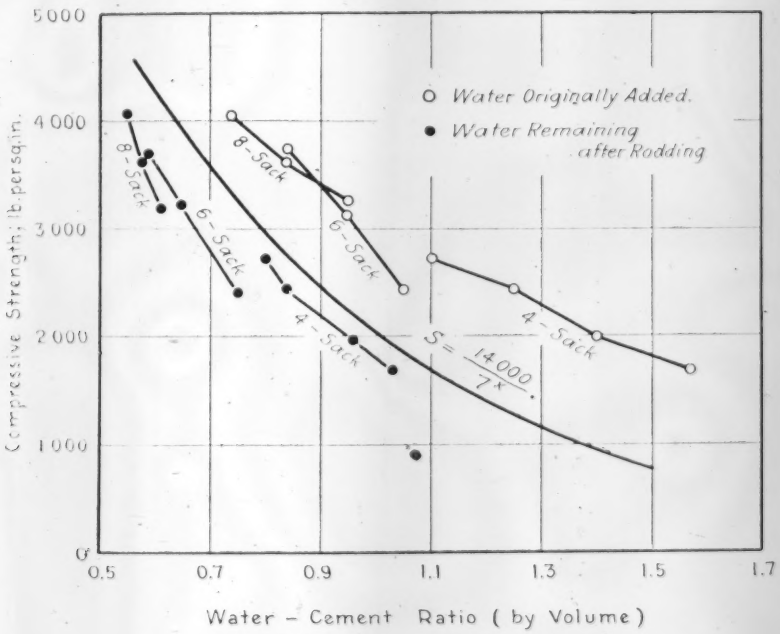


FIG. 4.—Relation between Compressive Strength and Water-Cement Ratio for Four, Six and Eight-Sack Concrete, Rodded Five Times, 1½-in Aggregate.

considerably higher than that of the concrete made at Lewis Institute. This difference is probably due neither to the difference in age nor to the difference in curing, as Mr. Walker found that the strength and the modulus of elasticity increase with age at approximately the same rate, and that storing the specimens in air instead of in moist sand reduces the modulus of elasticity as well as the strength.[2]

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 583 (1919).

[2] See p. 584 (*d*) and (*f*).

The writer believes that the higher value of the modulus found for rodded concrete is due to the rodding. It is evident from the tests in G. M. Williams' paper[1] that the modulus of elasticity increases as the flowability of the concrete decreases and it is evident from Fig. 4 that the flowability of concrete is

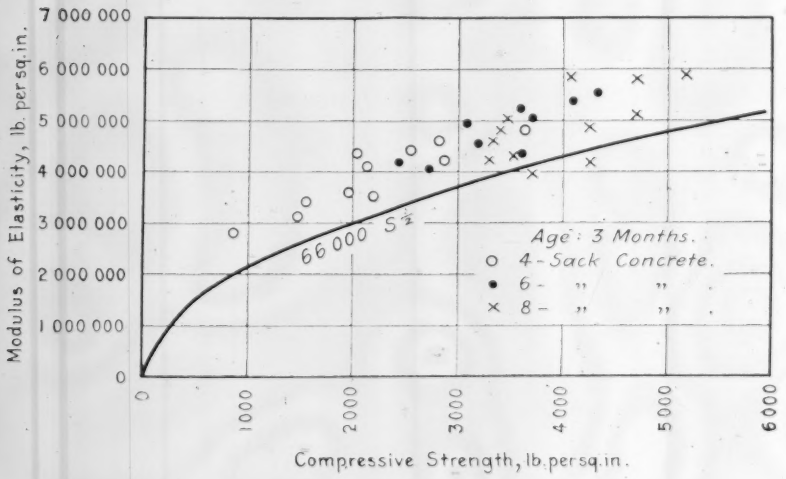


FIG. 5.—Modulus of Elasticity—Compressive Strength Relation for Rodded Concrete.

reduced materially by rodding. We should therefore expect an increase in the modulus of elasticity.

Fig. 5 indicates that the increase in the modulus of elasticity due to rodding is even greater than the increase in the compressive strength due to rodding.

[1] See p. 233.

DISCUSSION.

Mr. D. A. Abrams.—It is not clear to me just how the excess water removed by the rodding is to be disposed of on the job. If it is released, and undoubtedly it is desirable to have it released, naturally it must be disposed of and removed entirely from the member or the work. **Mr. Abrams.**

We made a number of tests a few months ago on the effect of pressure applied to fresh concrete. The tests showed clearly that pressure increases the strength of concrete and that the increase in strength is directly measured by the amount of the water expelled by the pressure. This is simply another way of accomplishing the results effected by rodding.

Mr. A. N. Talbot.—From the practical aspect, I think there may be applications of the method proposed. It was formerly followed to some extent in the construction of reinforced concrete columns. Rodding was practiced with good results with very wet concrete. I wish, however, to ask a question concerning the theoretical side of this. I believe that this paper is suggestive as indicating why an excess of water produces concrete which is not so dense and has less strength than has concrete in which less water was used. The writer of the paper refers to the escape of the entrapped air and the excess water, and thinks that in case of the rodded concrete a pressure is exerted on the concrete and the escape of the air is thereby facilitated. Is it his thought that this water remains around the particles of cement and aggregate in excess quantities because it has no avenue of escape, or because there is some superficial tension there that holds it and the pressure exerted upon the particles causes the water to move? That question may seem rather theoretical, but I, for one, have been searching for a reason why excess water remains. If more water is put in the concrete, it does not, itself, flow away. **Mr. Talbot.**

Mr. F. E. Giesecke.—Replying to Mr. Abrams, the excess water which is rodded out of field concrete can generally escape through openings in the forms or by flowing over the sides; to **Mr. Giesecke.**

Mr. Giesecke. facilitate this the forms should be filled so that the surface of the concrete is slightly higher than the forms.

Experiments at other institutions have also shown that the strength of concrete can be increased by subjecting the fresh concrete to pressure. In such an experiment at Lehigh University, the increase in the density of the concrete due to a pressure of about 200 lb. per sq. in. on the fresh concrete was practically the same as that secured in our laboratory by rodding, namely about 4 per cent. In field construction it is not practicable to subject fresh concrete to such a pressure, but it is easy to rod fresh concrete; the method of rodding is simple, cheap, and effective.

Replying to Mr. Talbot, when very wet concrete is used and simply deposited in the forms, a portion of the excess water rises to the surface and the concrete shrinks correspondingly; the remainder of the excess water is retained by the concrete. I believe the reason for this is that the pressure due to the difference between the weight of the cement and aggregate and that of the water is not sufficient to overcome the friction which must be overcome in order to force the excess water out before the concrete hardens; in addition, in some cases a relatively large quantity of water or of air lodges under the flat surface of the aggregate or of the reinforcing rods and is held there by an equal static pressure on all sides.

When rodding is applied to such concrete the particles of aggregate and the reinforcing steel are shifted sidewise and the water or air under the same can escape upward; in addition, a lateral pressure is applied to the concrete which squeezes some of the excess water out and compacts the concrete.

I believe the weakening effect of excess water on concrete is due principally to the production of a weaker cementing substance, probably by increasing the crystal and decreasing the colloid content of the same, and only in a small measure to the formation of a more porous concrete.

SOME DETERMINATIONS OF THE STRESS-DEFORMATION RELATIONS FOR CONCRETES UNDER REPEATED AND CONTINUOUS LOADINGS.

By G. M. Williams.

The deformation of concrete under stress, while of great importance in the design of reinforced concrete structures, is not generally given much consideration in tests of concrete. Although a definite value for the modulus of elasticity may be used in design, it is generally considered that the stress-deformation relation is not linear, even for small loads, and as a result such a value as is used is only an approximation which practice has shown to give safe results. Some authorities hold that the relation becomes linear for repeated applications of load, while others have found the linear relation only in concrete which has aged for a long period of time.

To find what the stress-deformation relation really is for various concretes made with our regular run of materials for different conditions, such as wet and dry, and for repeated and continuous applications of load, the work described later was undertaken.

Preparation of Concrete.

Unless stated otherwise, all determinations of the stress-deformation relations were made on concrete test cylinders 8 in. in diameter by 16 in. long stored in wet sand until the day of test. In all cases 6 by 12-in. specimens were prepared for test at 28 days, at which time the stress-deformation observations were started. The materials used were a standard Portland cement, Potomac River sand and gravel, and blast furnace slag. Just previous to testing, the specimens were removed from sand storage and the ends made plane and parallel by grinding on a steel plate with water and carborundum. All tests were made in a 200,000-lb. capacity testing machine having a spherical bearing block attached to the moving head, with the ends of the concrete specimen in direct contact with the metal head and weighing platform of the machine.

MEASUREMENT OF DEFORMATION.

An instrument consisting of two independent yokes, each having three points of contact with the surface of the test specimen, fitted with three Ames dial gages graduated to read to 0.0001 in., was used to measure the deformation under load.

FIG. 1.—Type of Instrument Used for Measuring Deformation of Specimen Under Load. It Consists of Two Independent Yokes Spaced 10 in. apart, Each Having Three Points of Contact with the Surface, and Fitted with Three Ames Dial Gages Graduated to Read to 0.0001 in.

As shown in Fig. 1, the yokes are spaced 10 in. apart so that the average deformation per inch can be determined to 0.000001 in. This instrument was designed by Mr. H. A. Davis, formerly with the Bureau of Standards. While this type of instrument requires a greater number of observations and considerably more computation than does the averaging type fitted with a

single dial, our experience would indicate that the former is generally more satisfactory and reliable since unequal deformations due to non-uniform loading is made apparent by unequal rate of movement of the dial hands. With the three-dial instrument, readjustment of position can immediately be made, while with the single-dial type such unequal loadings cannot be detected.

TYPE OF STRESS-DEFORMATION CURVE.

While it is true in a few cases that the first applications of load to a specimen will result in a curve which may be expressed

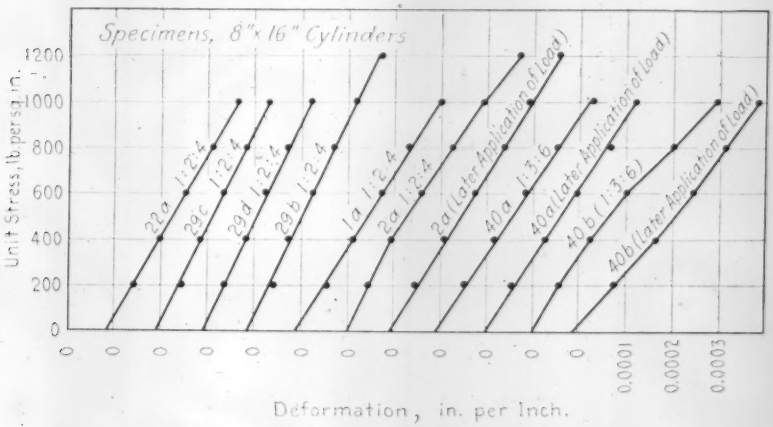


FIG. 2.—Typical Stress—Deformation Curves for Various Concretes Immediately After Removal from Wet Sand at Age of 28 Days. Curves Represent First Application of Load after Adjusting Deformeter.

by an exponential equation, this relation does not hold in any case for the concretes included in these tests for further application of load. Except in a few cases for 1 : 3 : 6 concretes at 28 days and wet-consistency 1 : 2 : 4 concrete at the same age, a straight line relation was obtained for the first application of load. A group of representative 1 : 2 : 4 and 1 : 3 : 6 concretes are included in Fig. 2. These specimens were all in a saturated condition at the time of test and three of the number, 2*a*, 40*a*, and 40*b*, showed increasing increments of deformation for constant increments of load for the first loading; but the removal of all

load and a later repetition of the loading resulted in a straight line relation for 2*a* and 40*a*. For 40*b*, later applications of load repeatedly resulted in greater increments for the smaller loads than were obtained for the greater loads, giving a curve as shown at the right of the diagram in Fig. 2. In general the

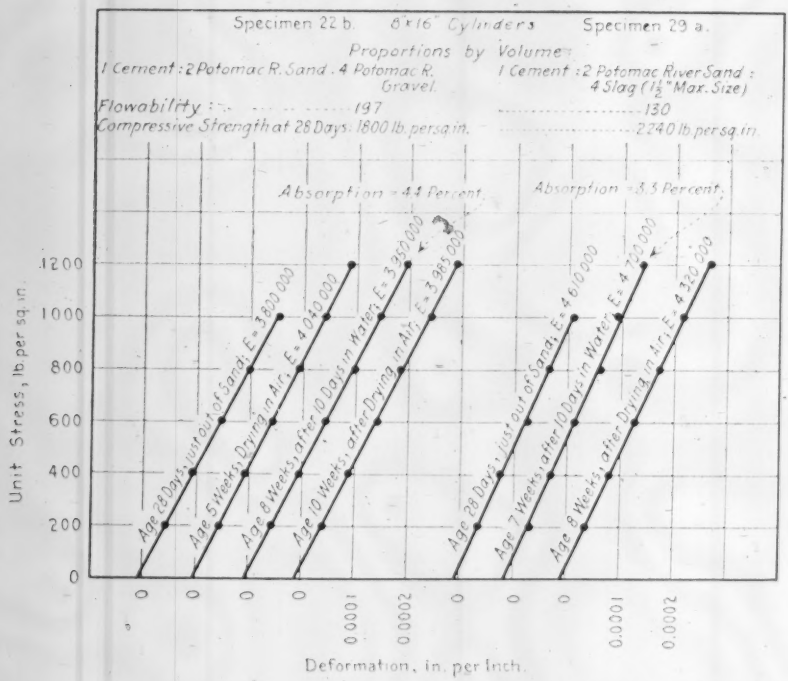

Specimen 22 b. 8 x 16" Cylinders
Specimen 23 a.
Proportions by Volume:
1 Cement : 2 Potomac R. Sand : 4 Potomac R. Gravel.
1 Cement : 2 Potomac River Sand : 4 Slag (1½" Max. Size)
Flowability : 197
..... 130
Compressive Strength at 28 Days: 1800 lb. per sq. in.
..... 2240 lb. per sq. in.
Absorption = 4.4 Percent.
Absorption = 3.3 Percent.
Age 28 Days, just out of Sand; E = 3,820,000
Age 5 Weeks, Drying in Air; E = 4,040,000
Age 8 Weeks, after 10 Days in Water; E = 3,950,000
Age 10 Weeks, after Drying in Air; E = 3,950,000
Age 28 Days, just out of Sand; E = 4,610,000
Age 7 Weeks, after 10 Days in Water; E = 4,720,000
Age 8 Weeks, after Drying in Air; E = 4,320,000
Unit Stress, lb. per sq. in.
1200
1000
800
600
400
200
0
0
0.0001
0.0002
Deformation, in. per Inch.

FIG. 3.—Modulus of Elasticity of Concrete in Dry and Wet Condition for Loads in Excess of Usual Working Loads. Determinations Were Made at 28 Days When Specimens Were Removed from Wet Sand, after Drying in the Air, after Immersion in Water for a Period of 10 Days, and Again after Drying in Air.

deformation for a unit stress of 200 lb. per sq. in. is less than that obtained for further equal increments of stress so that a straight line drawn through the values for the higher loads will fall slightly to the left of the origin. The curves shown for later applications of load were obtained with the instrument in position as originally placed. The true stress-deformation curve

as represented in Fig. 2 and following figures should be shown for such cases with a curve from the deformation at 200 lb. to the origin. However, since the computation of the value of the modulus of elasticity involves the slope of the line, the curves have in all cases been drawn straight to the line of zero load for convenience. The shape of the curve, however, for loadings less than 200 lb. per sq. in. has no practical significance.

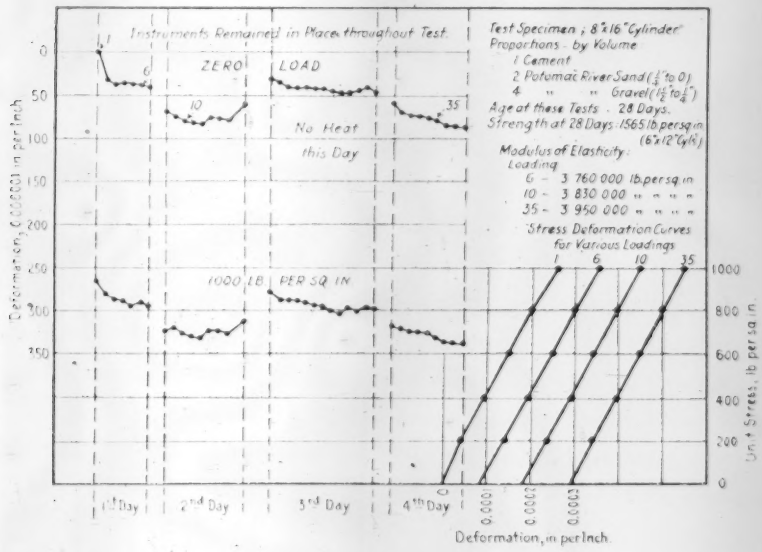

Instruments Remained in Place throughout Test.
ZERO
LOAD
No Heat this Day
1000 LB PER SQ IN
1 Day
2nd Day
3rd Day
4th Day
Deformation, in per Inch
Unit Stress, lb per sq in
Test Specimen; 8"x16" Cylinder
Proportions - by Volume
1 Cement
2 Potomac River Sand (¼" to 0)
4 " " Gravel (½" to ⅝")
Age at these Tests - 28 Days.
Strength at 28 Days - 1565 lb per sq in (6"x12" Cyls)
Modulus of Elasticity:
Loading
6 - 3 760 000 lb per sq in
10 - 3 830 000 " " " "
35 - 3 950 000 " " " "
Stress Deformation Curves for Various Loadings
1
6
10
35

FIG. 4.—Deformation of Concrete under Repeated Applications of Loads in Excess of the Usual Working Loads.

MODULUS OF ELASTICITY, E, OF CONCRETE FOR WET AND DRY CONDITION.

In Fig. 3 are shown representative stress-strain relations for concrete in the wet and dry condition. Specimen 22*b* at the age of 28 days, when removed from wet sand storage, had a modulus of elasticity, E, of 3,800,000 lb. per sq. in.; one week later after drying in air the value for E was 4,040,000. At the age of 8 weeks, after 10 days immersion in water, during which time the specimen absorbed 4.4 per cent by weight, the value for E was 3,950,000. After further drying in air for 2 weeks

the value obtained was 3,985,000. For specimen 29*a*, in which slag was used as a coarse aggregate, the value after removal from damp sand was 4,610,000 lb. per sq. in.; after 10 days in water, 4,700,000; and after drying for 1 week in air, 4,320,000 lb. per sq. in. The range of values in both cases are no greater than would be expected for repeated removal and replacement

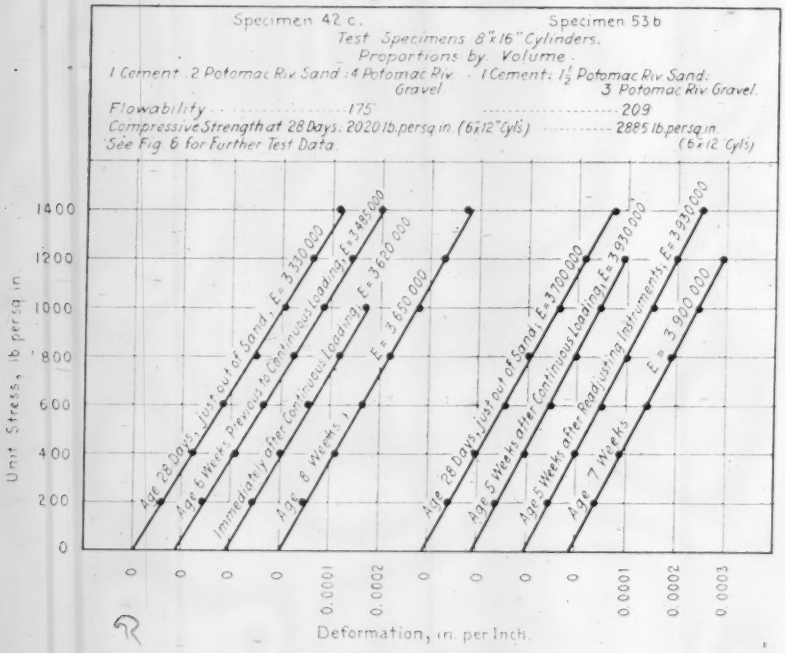

Specimen 42 c.
Specimen 53 b
Test Specimens 8"x16" Cylinders.
Proportions by Volume.
1 Cement : 2 Potomac Riv. Sand : 4 Potomac Riv. Gravel
1 Cement : 1½ Potomac Riv. Sand : 3 Potomac Riv. Gravel
Flowability 175 209
Compressive Strength at 28 Days: 2020 lb. per sq. in. (6x12" Cyls) ..... 2885 lb. per sq. in. (6x12 Cyls)
See Fig. 6 for further Test Data.
Unit Stress, lb. per sq. in.
1400
1200
1000
800
600
400
200
0
Age 28 Days, just out of Sand, E = 3,330,000
Age 6 Weeks, Previous to Continuous Loading, E = 3,485,000
Immediately after Continuous Loading, E = 3,620,000
Age 8 Weeks, E = 3,650,000
Age 28 Days, just out of Sand, E = 3,700,000
Age 5 Weeks after Continuous Loading, E = 3,930,000
Age 5 Weeks after Readjusting Instruments, E = 3,930,000
Age 7 Weeks, E = 3,900,000
0 0 0 0 0.0001 0.0002
0 0 0 0 0.0001 0.0002 0.0003
Deformation, in. per Inch.

FIG. 5.—Modulus of Elasticity of Concrete before and after Continuous and Repeated Applications of Loads in Excess of the Usual Working Loads. Tests Were Started at the Age of 28 Days Immediately after Removal from Wet Sand Storage.

of instruments for a specimen stored under uniform and constant conditions of humidity. Further data showing similar constant values for the wet and dry condition are contained in Figs. 4, 5 and 6.

DEFORMATION OF CONCRETE UNDER REPEATED LOADS.

In Fig. 4 are shown the results of repeated applications of load on a specimen of 1 : 2 : 4 concrete which had a strength of

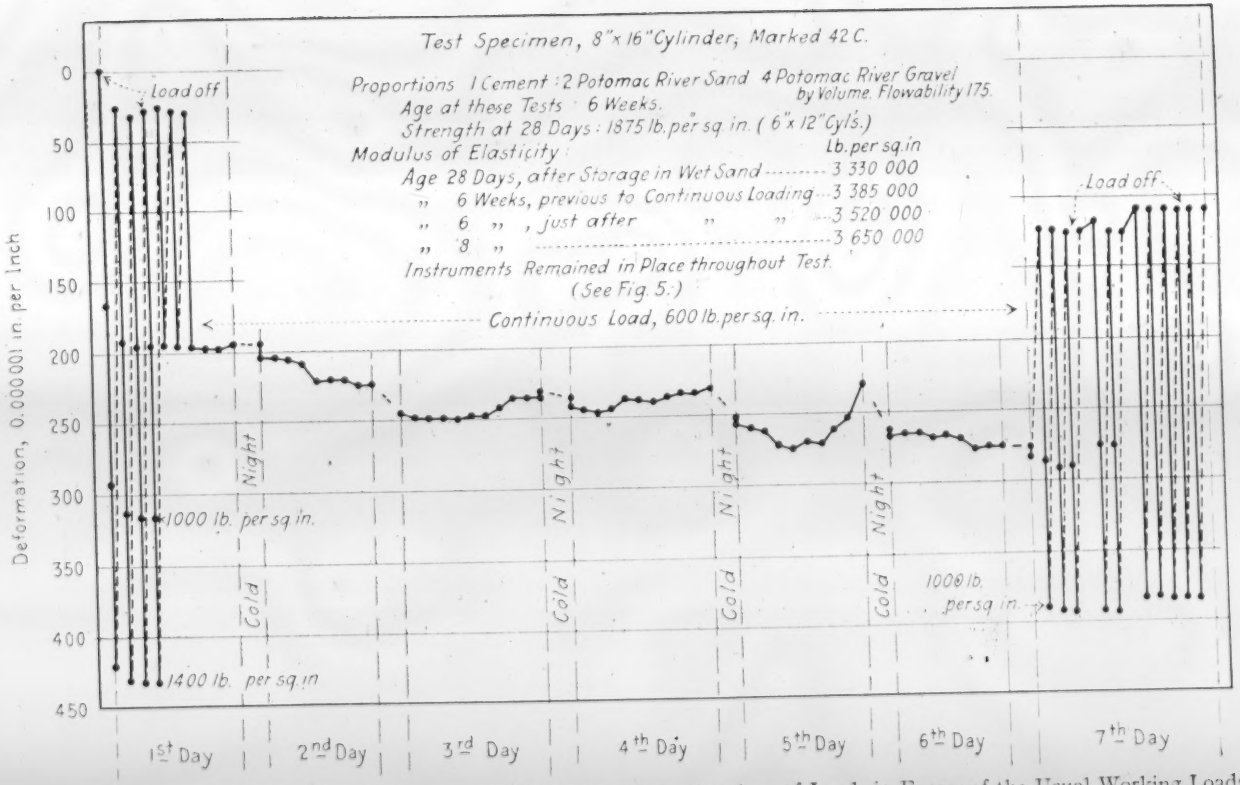


FIG. 6.—Deformation of Concrete under Repeated and Continuous Applications of Loads in Excess of the Usual Working Loads.

1565 lb. per sq. in. at 28 days as determined by tests of 6 by 12-in. cylinders. All load was removed in every case after the maximum of 1000 lb. per sq. in. was applied. The lines for "zero load" and "1000-lb.-per-sq.-in. load" may be considered as the elevation of the upper surface of the cylinder during the progress of the test. Load was first applied immediately after removal from wet sand with the result as shown in the stress-deformation curve marked 1 at the right of the diagram. Load was released and a permanent set of about 0.000033 in. per inch was noted. Further applications of load equal to two-thirds of the ultimate strength of the specimen showed very slight increase in set beyond that resulting from the first application. Standing over night with no load, temperature changes gave readings the next morning which seemed to indicate nearly as great a permanent set as resulted from all applications of loads the day previous. The modulus of elasticity for loading No. 10 is slightly higher than for loading No. 6 the previous day. The turning off of the heat in the afternoon of the second day is shown by the last load applied late in the evening of that day. On the third day there was no heat; but the repeated application of loads together with the direct rays of the sun later in the day gradually increased the permanent set and caused corresponding increases in the deformation for maximum load. Late on the fourth day the permanent set for zero load was approximately the same as for the second day.

Continued repetitions of load tend to raise slightly the value of the modulus of elasticity. In the case of specimen 42*b*, the value for E gradually increased during the test, becoming 3,950,000 lb. per sq. in. for the 35th loading on the fourth day. It should be noted that these loadings are well beyond the strengths ordinarily assumed in design for concrete of this quality.

DEFORMATION OF CONCRETE UNDER CONTINUOUS LOAD.

The deformation of concrete under repeated loads and continuous loads is illustrated in Figs. 5 and 6. Specimen 42*c*, made of 1 : 2 : 4 concrete having a compressive strength of 2020 lb. per sq. in. at 28 days, was placed in the machine immediately after removal from wet sand, and the value for

the modulus of elasticity was found to be 3,330,000 lb. per sq. in. After drying in the air for 2 weeks, the value was determined as 3,485,000. After a number of loadings up to 1400 lb. per sq. in., during which the preceding value was obtained, a load equivalent to 600 lb. per sq. in. was maintained for seven days. The gradual permanent set of the concrete as well as the resultant of temperature changes is indicated by the dotted line across the center of Fig. 6. The effect of temperature change due to the turning off of the steam heat each afternoon is indicated by the rise of the curve at the end of each day. This was especially marked for the fifth day when the night was unusually cold. Each morning the beam was found dropped, and a load equivalent to from 10 to 15 lb. per sq. in. was usually required to balance it. During the day, the higher temperature in the room in several cases caused the beam to rise so that the actual load would be approximately 6 lb. per sq. in. more than had been applied originally through the machine. On the seventh day, all load was released and repeated loadings of 1000 lb. per sq. in. were applied. As shown in Fig. 5 the modulus increased slightly to 3,520,000. After storage in air for one week, further loadings to 1400 lb. per sq. in. gave a value of 3,650,000.

As shown in Fig. 5, similar results were found for specimen 53*b*, a 1 : $1\frac{1}{2}$: 3 proportion concrete which had a strength of 2885 lb. per sq. in. at 28 days. In this case a constant load of 1000 lb. per sq. in. was applied for a period of six days with detailed results quite similar to those shown in Fig. 6 for the 1 : 2 : 4 proportion concrete.

MODULUS OF ELASTICITY FOR PROPORTIONS RANGING FROM NEAT CEMENT TO 1 : 3 : 6 CONCRETES FOR THE EXTREME RANGES OF CONSISTENCIES COMMONLY USED IN PRACTICE.

The data shown in the preceding groups were obtained from tests of various concretes prepared over a period of time in the concrete laboratory of the Bureau of Standards and while giving definite information as to the properties studied are of little value in indicating the extreme range of values which will result from wide variations in cement content and in consistencies

for the same cement and aggregate. It is clear from a study of test data that the only function and value of aggregate in a concrete, so far as compressive strength is concerned, is to furnish an economical mixture as compared with the cost of neat cement, and that some strength under such conditions results, not because of the presence of the aggregate, but in spite of its presence in the mix. In other words, cement is the one strength-giving element in the mix and aggregate is used only for the sake of economy.

With this point in view, concretes were prepared ranging in cement content from neat cement to 1:3:6, having two consistencies or flowabilities.

These concretes were composed of a normal Portland cement, Potomac River sand passing the $\frac{1}{4}$-in. screen, and Potomac River gravel passing the $\frac{3}{4}$-in. screen. Sand and gravel were proportioned by volume in a cubic-foot measure, the materials being taken from stock piles which had just previously been wet by rains. Cement was weighed to insure the same quantity for each batch. Mixing was continued for two minutes in a batch mixer for the concretes and four minutes for the neat cement pastes. The above procedure was followed to duplicate in every way possible the best control which might be employed in the field when using the same materials.

Consistency was controlled and measured by means of the "flow table" which has been employed for this purpose in the concrete laboratory of the Bureau of Standards since the early part of 1919. Flowability is measured by the increase in diameter of a mass of concrete molded in the shape of a frustum of a cone on a table top which may be raised and dropped through a fixed distance by means of a cam. As shown in Fig. 7, a mass of concrete 6 in. high having upper and lower diameters of 8 and 12 in., respectively, is molded on the metal covered top, the form withdrawn and the table top raised and dropped 15 times through a distance of $\frac{1}{2}$ in. The mass usually spreads concentrically; and two diameters at right angles, the long and short ones if difference is apparent, are measured by means of a proportional caliper which is graduated in such a manner that the sum of the two readings gives what is called "relative flowability." This figure is always greater than 100 and is obtained

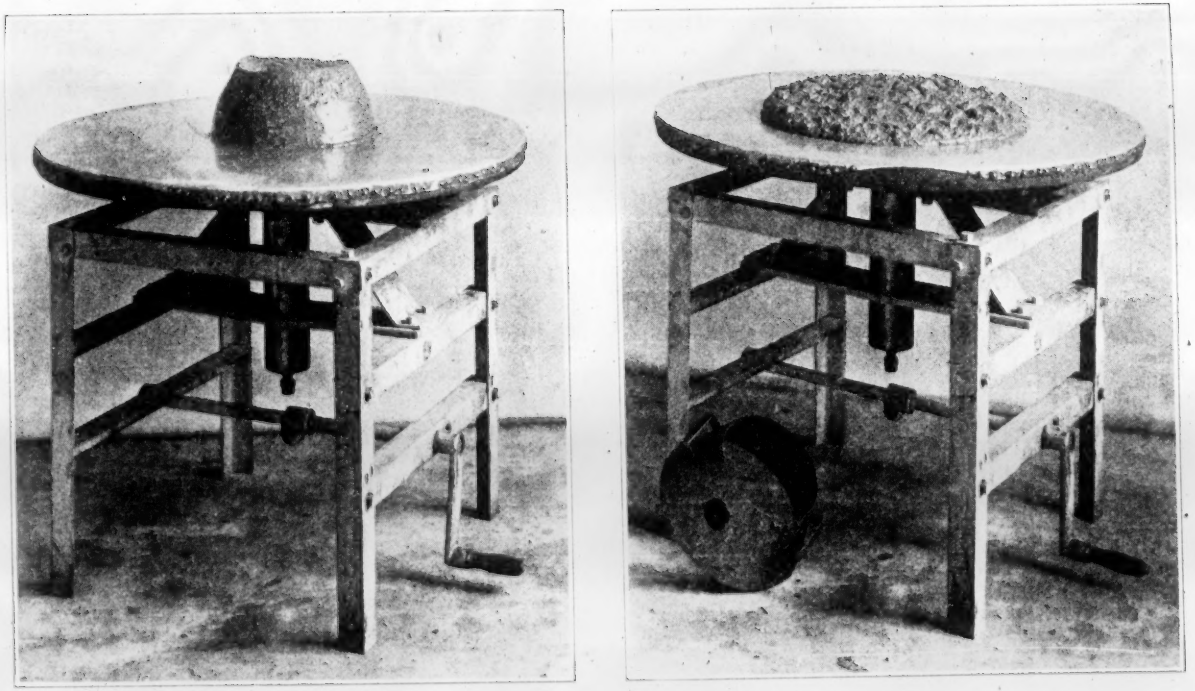


FIG. 7.—Flow Table for Measuring the Flowability of Concrete.

Table Top Can Be Raised Vertically a Fixed Distance Controlled by a Set Bolt at the Bottom of the Vertical Shaft, by Means of a Cam and allowed to Drop Freely. First View Shows 1:½:3 Concrete in Place for Test with the Mold Removed. Second View Shows the Mass Flattened Concentrically after 15 Drops of the Top Through a Distance of ½ in. Flowability is 170 for the Mass Shown. Such a Consistency is About the Stiffest Which Can Be Properly Placed in Reinforced Concrete Work.

by dividing the new diameter of the mass by the old and multiplying by 100. Tests have shown that flowability is directly proportional to the percentage of mixing water by weight of dry materials in any mass; also that flowability as measured by the "flow table" varies directly with the velocity of flow in a steel chute for all usable and workable concretes.[1]

In these tests the total amount of water used was deter-

TABLE I.—MODULUS OF ELASTICITY AND COMPRESSIVE STRENGTH OF CONCRETES OF DIFFERENT PROPORTIONS AND TWO FLOWABILITIES.

POTOMAC RIVER MATERIALS—SAND 0 TO ¼ IN., GRAVEL ¼ TO ¾ IN. STORED IN WET SAND FOR 27 DAYS.

Relative Flowability.	Proportions by Volume	Modulus of Elasticity, 8 by 16-in. Cylinders, lb. per sq. in.		Compressive Strength, lb. per sq. in. at 28 days. Average of three 6 by 12-in. cylinders.	Ratio, Modulus of Elasticity to Compressive Strength.
		Individual.	Average.		
165[a]	Neat Cement	3 640 000 3 750 000	3 695 000	7860	470
	1 : 1 : 2	3 685 000 3 780 000	3 732 500	3220	1160
	1 : 1½ : 3	3 485 000 3 410 000	3 447 500	2805	1230
	1 : 2 : 4	3 010 000 3 075 000	3 042 500	2010	1515
	1 : 3 : 6	2 490 000 2 620 000	2 555 000	1080	2370
240[a]	Neat cement	3 540 000 3 570 000	3 555 000	9285	386
	1 : 1 : 2	3 430 000 3 240 000	3 335 000	3070	1085
	1 : 1½ : 3	3 200 000 3 150 000	3 175 000	2425	1310
	1 : 2 : 4	2 850 000 2 870 000	2 860 000	1850	1545
	1 : 3 : 6	1 895 000 1 770 000	1 832 500	800	2290

[a] Relative flowability of 165 is about the driest which can be used in reinforced concrete work. A relative flowability of 240 is as fluid a mix as need be used. For this particular combination of aggregates the addition of much more water would have caused excessive segregation, especially for the leaner proportions.

mined as carefully as possible by drying representative samples of the wet sand and gravel, but as is true in practice, the actual amount used is of no consequence, since a definite flowability was desired and as much water was added as would result in the required consistency.

The two flowabilities used, 165 and 240, represent the extremes which would ordinarily be used in practice in structural work. A flowability of 165 is too low to permit placing through

[1] See *Engineering News-Record*, May 27, 1920, for a more complete description of the "flow table."

ordinary chute systems, while a flowability of 240 is as great as is generally needed in practice. The addition of more mixing water would result in considerable segregation for this particular combination of fine and coarse aggregates.

For modulus of elasticity determinations, two 8 by 16-in. cylinders were prepared from each batch and three 6 by 12-in. cylinders were molded for test at 28 days. All specimens were

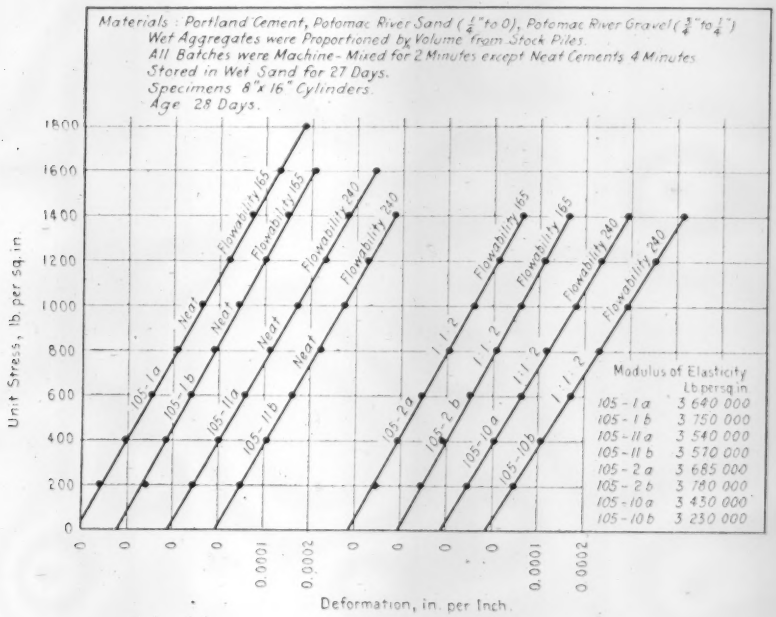

Materials: Portland Cement, Potomac River Sand (¼" to 0), Potomac River Gravel (¾" to ¼")
Wet Aggregates were Proportioned by Volume from Stock Piles.
All Batches were Machine-Mixed for 2 Minutes except Neat Cements, 4 Minutes.
Stored in Wet Sand for 27 Days.
Specimens 8" x 16" Cylinders.
Age 28 Days.
Unit Stress, lb per sq. in.
Deformation, in. per Inch.
105-1a Neat Flowability 165
105-1b Neat Flowability 165
105-11a Neat Flowability 240
105-11b Neat Flowability 240
105-2a 1:1:2 Flowability 165
105-2b 1:1:2 Flowability 165
105-10a 1:1:2 Flowability 240
105-10b 1:1:2 Flowability 240
Modulus of Elasticity Lb per sq. in.
105-1a 3 640 000
105-1b 3 750 000
105-11a 3 540 000
105-11b 3 570 000
105-2a 3 685 000
105-2b 3 780 000
105-10a 3 430 000
105-10b 3 230 000

FIG. 8.—Modulus of Elasticity of Neat Cement and 1:1:2 Concrete Varying as Widely in Flowabilities as Are Commonly Used in Structural Work.

stored in wet sand for 27 days, after which they were removed and the test results shown in Figs. 8, 9 and 10 obtained. These data are also shown in tabular form in Table I.

As would be expected, compressive strengths and values of the modulus of elasticity are lower for the flowability of 240 than for that of 165, except for the dry neat cement mix. The only explanation which can be offered for this discrepancy is the possibility that insufficient work was done on the mass to

result in the plastic condition which is attained in laboratory tests of neat cement only after a minute or more of vigorous working of a small lot of material. A flowability of 165 for this material did not result in a plastic mass but a large ball was formed, which rolled around without the distortion of the mass which is necessary to obtain the required plasticity. The higher flowability of 240 resulted in a mass which readily flowed

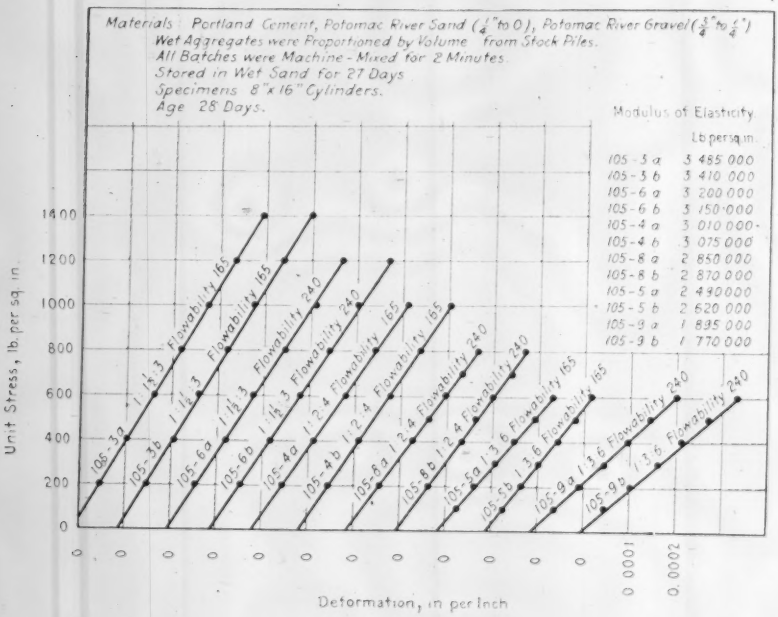

Materials: Portland Cement, Potomac River Sand (¼" to 0), Potomac River Gravel (¾" to ¼")
Wet Aggregates were Proportioned by Volume from Stock Piles.
All Batches were Machine-Mixed for 2 Minutes.
Stored in Wet Sand for 27 Days.
Specimens 8"x16" Cylinders.
Age 28 Days.
Modulus of Elasticity
Lb per sq in.
105-3 a 3 485 000
105-3 b 3 410 000
105-6 a 3 200 000
105-6 b 3 150 000
105-4 a 3 010 000
105-4 b 3 075 000
105-8 a 2 850 000
105-8 b 2 870 000
105-5 a 2 490 000
105-5 b 2 620 000
105-9 a 1 895 000
105-9 b 1 770 000
Unit Stress, lb per sq in.
Deformation, in per Inch
0.0001
0.0002

FIG. 9.—Modulus of Elasticity of 1:1½:3, 1:2:4 and 1:3:6 Concretes Varying as Widely in Flowabilities as Are Commonly Used in Structural Work.

in the mixer. Reference to Fig. 10 indicates that the modulus for the dry mix is lower than would have resulted had the proper amount of work been done on the mass.

In Fig. 8 are shown the stress deformation relations for the neat and 1 : 1 : 2 proportion test specimens. The results of determinations on the 1 : 1½ : 3, 1 : 2 : 4 and 1 : 3 : 6 concretes are shown in Fig. 9. It is noticeable that there is a general lowering of the modulus with increase in flowability of the mix

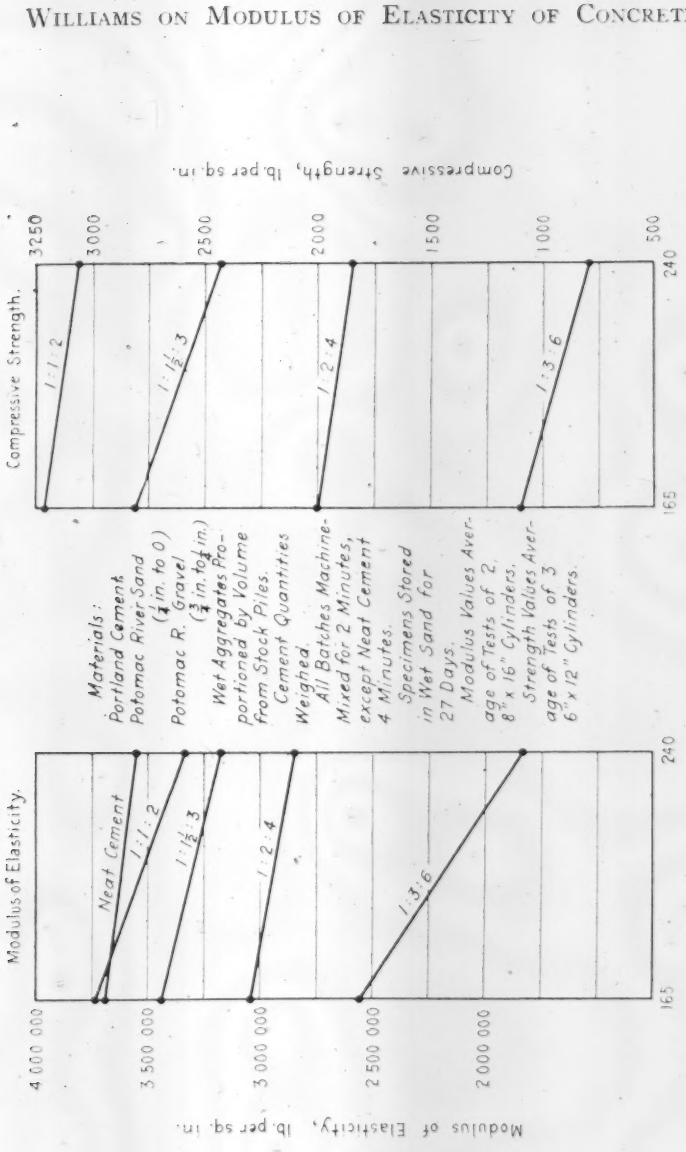


FIG. 10.—Compressive Strengths and Moduli of Elasticity of Concretes of Two Consistencies and Five Proportions Varying from Neat Cement to 1:3:6.

and decrease in cement content, although this change is by no means proportional to change in cement content.

The results of both modulus of elasticity determinations and strength tests are shown in Fig. 10. The strength values of the neat cement specimens are omitted in order to avoid great reduction in the strength scale. For these given aggregates it is seen that the relation between modulus of elasticity and compressive strength is fairly definite for both flowabilities of any one proportion, the ratio increasing with leanness of the mix. Other tests have shown that these ratios will be modified by changes in maximum size of particles in the coarse aggregate, so that the actual values shown are representative only for the materials used.

SUMMARY.

The data of which the preceding may be considered representative bears out the results of tests previously made in our laboratory that:

1. The true stress-deformation relations for concrete under loads even exceeding designing loads and loads applied in practice and up to 50 or 75 per cent of the ultimate strength may be represented by a straight line.

2. For a few specimens, composed of lean-mix or very wet-consistency concretes just removed from damp sand storage, it was found that the increments of deformation for equal increments of load for the first application of load only could be represented by an equation of the exponential type, but second and additional applications of load resulted in a straight line relation.

3. For ordinary working loads, and up to 50 to 70 per cent of the ultimate strength of the concrete, 95 per cent of the value for modulus of elasticity obtained by dividing the unit stress by the unit deformation for that load will represent the true modulus with sufficient accuracy.

4. The modulus of elasticity for normal concretes is the same for any given material in either the wet or dry condition.

5. The modulus of elasticity of concrete is apparently increased slightly for repeated or long continued single applications of loads. The modulus of elasticity of concrete in a

structure subjected to loads within design limits is probably slightly greater than the value found from tests of cylindrical specimens of the same concrete. The stress-deformation relation under such conditions can be represented by a straight line.

6. With any given cement and grading of aggregate of the same maximum size, and for any given proportion of cement to aggregate, the ratio of modulus of elasticity to compressive strength of concrete is fairly constant, regardless of the consistency or flowability.

DISCUSSION.

Mr. Walker.

MR. STANTON WALKER (*presented in written form*).—It is worth noting that Mr. Williams is in disagreement with most investigators when he concludes that the stress-deformation relation for concrete is linear for stresses lower than 50 to 70 per cent of the ultimate strength of the concrete.

In a paper on the modulus of elasticity of concrete which the writer presented to this Society[1] in 1919, data from tests made at the Structural Materials Research Laboratory, Lewis Institute, Chicago, were presented which showed that the stress-deformation relation for concrete may be represented by an exponential equation of the form

$$S = Kd^n \qquad (1)$$

where S = compressive stress in concrete, d = unit deformation of concrete, K = a constant, depending on the strength of the concrete, n = an exponent, approximately the same for all conditions.

In Table I stress-deformation data are tabulated for four different concrete mixtures. Each value for strength and deformation is the average of 80 tests of 6 by 12-in. cylinders made on 20 different days. The specimens were made and tested in accordance with our regular laboratory practice. The materials, the method of molding, and the condition of storage were alike for all specimens. The method of testing was the same in all cases except that for each mix deformations were measured over four different gage lengths; 20 specimens were tested using a 4-in. gage length, 20 using a 6-in. gage length, 20 with an 8-in. gage length, and 20 with a 10-in. gage length. It was considered proper to average the unit deformation obtained for the different gage lengths since they were essentially the same. The deformations were measured by means of an averaging compressometer[2] equipped with a 0.0001-in. Ames dial.

These data are platted in Fig. 1. The solid lines represent

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

[2] For a description of this instrument see *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 519 (1919).

the experimental values. It will be noted that all of them show a slight curvature. The constants for Eq. 1 were calculated for the solid lines and the corresponding graph is shown by the dotted lines. The deformations calculated from Eq. 1 are also tabulated in Table I. It will be seen that there is an almost exact agreement between the experimental and calculated values. **Mr. Walker.**

We have in our files sufficient data to give thousands of examples corroborating the information brought out by these tests. The vast majority of all our data would indicate that

TABLE I.—STRESS-DEFORMATION RELATION FOR CONCRETE.

(Data from Series 99)

Compression tests of 6 by 12-in. cylinders.
Hand-mixed concrete.
Mix by volume. Relative consistency 1.00.
Cement: a mixture of four brands purchased in the Chicago market.
Aggregate: sand and pebbles from Elgin, Ill., graded 0–1½ in.
Specimens stored in damp sand, tested damp.
Each value is the average of 80 tests made on 20 different days.
Deformations were measured for 20 tests, each over 4 different gage lengths.

Unit Compressive Stress, lb. per sq. in.	Unit Deformation, in. per inch.							
	Mix 1:7 by Volume.		Mix 1:5 by Volume.		Mix 1:4 by Volume.		Mix 1:3 by Volume.	
	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.	Experimental.	Calculated.
100	0.000020	0.000020	0.000019	0.000019	0.000017	0.000017	0.000018	0.000018
200	47	47	43	43	39	39	39	40
300	74	77	67	70	62	64	62	65
400	109	110	95	100	87	91	89	92
500	144	144	129	129	119	118	112	118
600	182	180	162	160	150	148	146	146
700	224	220	194	192	177	177	178	175
800	264	258	228	221	208	208	207	205
900	312	300	264	254	239	240	242	228
1000	376	330	319	285	282	270	294	265
Ultimate strength, lb. per sq. in.	1780		2580		3120		3480	

the usual form of the stress-deformation relation for concrete is curvalinear throughout the entire range in stress.

It would seem to the writer that the tests from which Mr. Williams concludes that the modulus of elasticity of wet and dry concrete is the same, other conditions being equal, are open to two serious objections:

1. The age of the concrete varied from 4 to 10 weeks; it is an established fact that concrete 10 weeks old should be stronger than that 4 weeks old;

Mr. Walker.

2. The concrete had been loaded one or more times previous to test for all conditions but one—the test at four weeks.

It would seem that these variables create a sufficient confusion of conditions to cast doubt on the author's conclusions.

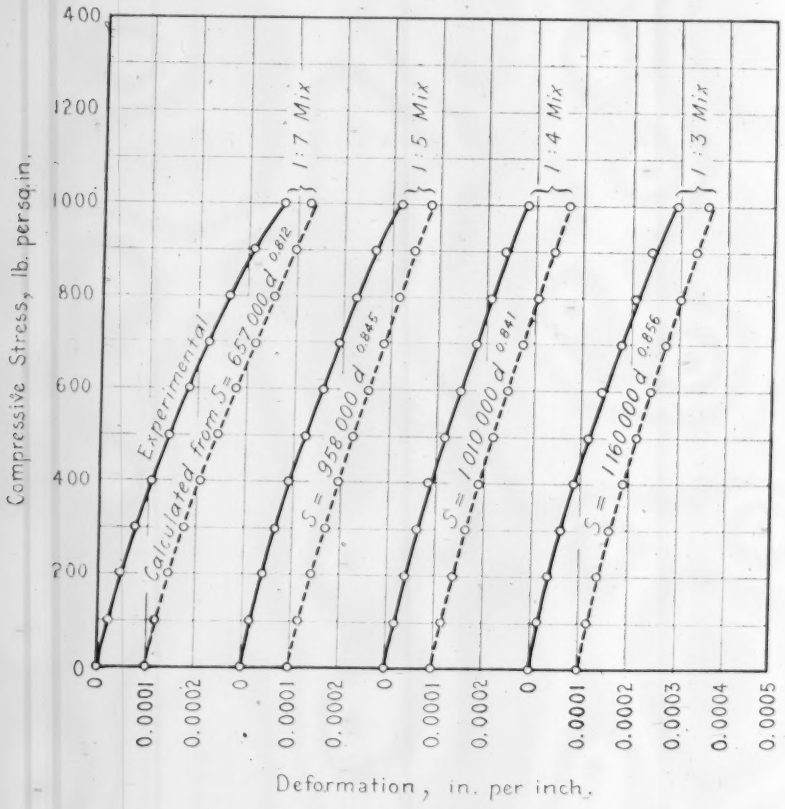


FIG. 1.—Stress-Deformation Relation for Concrete.

Compression tests of 6 by 12-in. cylinders.
Mix by volume; aggregate sand and pebbles graded 0–1½ in.
Relative consistency of concrete 1.00.
Specimens stored in damp sand, tested damp.
Each value is the average of 80 tests made on 10 different days.

The necessity of loading the specimens more than once might have been eliminated by making a number of test-pieces under the same conditions and dividing them into groups for

the different storage conditions. The effect of the difference in age of the concrete could have been made negligible by testing the concrete at such a time that the period required for drying out or saturating the specimens would have been only a small percentage of the age at tests. Following are the results of such a group of tests: Mr. Walker.

The "wet" specimens were stored in damp sand until tested at the age of one year. The "dry" specimens were stored in damp sand one year and then allowed to dry in the air of the laboratory for one month. They were tested at the age of 13 months. Each value is the average of 5 tests made on 5 different days. The mix was 1:4 by volume. The aggregate was 0–1½-in. sand and pebbles. The consistency was similar to that usually used in concrete road construction.

	"WET" CONCRETE, STORED 1 YEAR IN DAMP SAND.	"DRY" CONCRETE, STORED 1 YEAR IN DAMP SAND, 1 MONTH IN AIR.
Initial tangent modulus of elasticity, lb. per sq. in.	7 450 000	9 320 000
Compressive strength, lb. per sq. in.	4 950	5 920

It will be noted that both the strength and modulus of elasticity are higher for the dry concrete.

Mr. M. B. Lagaard reported data in the *Engineering News-Record*[1] which confirms the above results. Fig. 2 is a reproduction of Fig. 5 of Mr. Lagaard's article.

The deformations were measured, by means of a four-dial compressometer, on 8 by 16-in. concrete cylinders over a 10-in. gage length. The readings could be estimated to 0.0001 in.

The curve of deformations for the "wet" concrete is below that for the "dry" concrete, from the first application of load until failure.

In Fig. 3, data given in Table I of Mr. Williams' paper are platted with the unit compressive strength as abscissæ and the modulus of elasticity as ordinate. The values for the neat cement mixture were omitted because Mr. Williams calls attention to the fact that they are erratic, and because we have found

[1] M. B. Lagaard, "Saturation of Concrete Reduces Strength and Elasticity," *Engineering News-Record*, November 14, 1918, p. 908.

Mr. Walker. in our studies that mixtures richer than about 1:3 do not conform to the general relation.

Fig. 4, shows a similar relation for our tests. This figure is the same as Fig. 25 in the paper on Modulus of Elasticity of Concrete mentioned above.

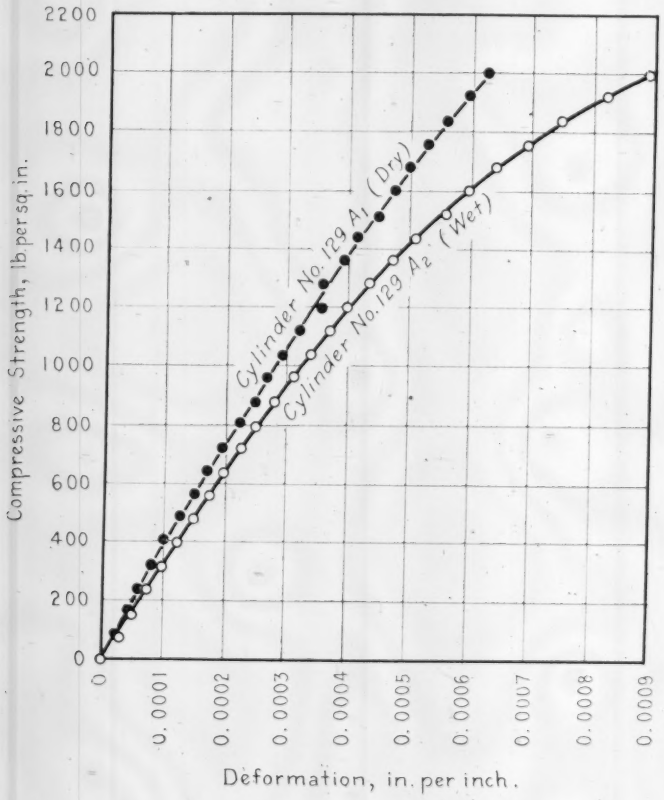


FIG. 2.—Effect of Moisture Content in Concrete on its Modulus of Elasticity.

From Article by M. B. Lagaard in *Engineering News-Record*, November 14, 1918.

Compression tests of 8 by 16-in. concrete cylinders.
1:2:4 limestone concrete.

Cyl. No.	Age at Test, days.	Storage Condition.	Modulus of Elasticity, lb. per sq. in. (at 600 lb.)	Compressive Strength, lb. per sq. in.
129 A_1	469	7 days under wet sacks and 462 days in air.....	3 700 000	3630
129 A_2	462	7 days under wet sacks, 434 days in air, 21 days in water.....	3 150 000	2340

Mr. Walker.

From the relation found in Figs. 3 and 4 we are inclined to believe that had Mr. Williams investigated concretes of a wider range in flowability, using aggregates with a considerable difference in the proportion of sand, he would not have formed the conclusion that for a given mix and size of aggregate "the ratio of modulus of elasticity to compressive strength of concrete is fairly constant, regardless of the consistency or flowability."

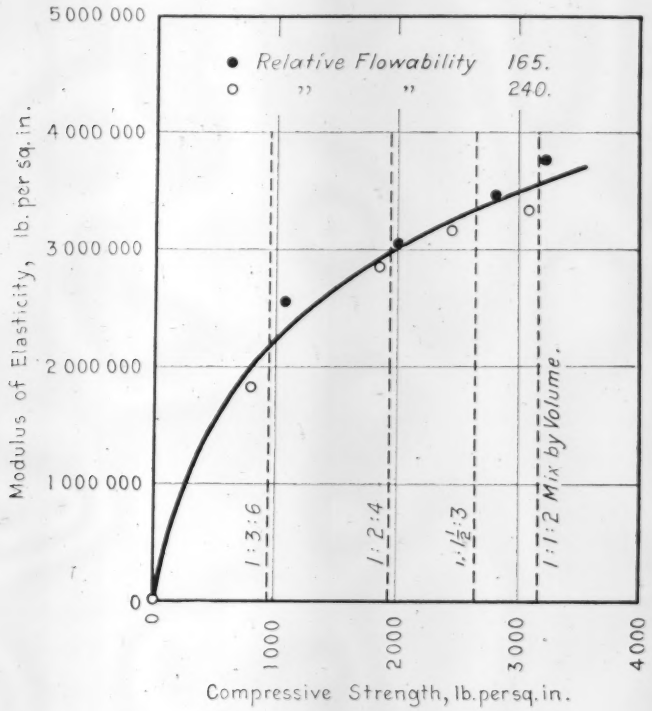


FIG. 3.—Relation of Modulus of Elasticity to Strength of Concrete.
Data from Table I of Williams' paper.

Although Mr. Williams did not report the quantities of water used, a narrow range is indicated from the fact that concrete of the dry consistency has a strength only 5 per cent higher than the wet consistency for the 1:1:2 mix, 16 per cent higher for the 1:1½:3, 9 per cent for the 1:2:4, and 35 per cent for the 1:3:6 mix.

Mr. Walker. Table II gives the ratio of Initial Tangent Modulus of Elasticity to Compressive Strength calculated from the results of tests in Table XIII in our paper on the Modulus of Elasticity of Concrete. The test specimens were 6 by 12-in. cylinders and were stored in damp sand until tested at 28 days. The aggregate was 0–$1\frac{1}{2}$ in., sand and pebbles. Each value is the average of five tests made on different days.

In the same table data are given for a 1:5 mix, using 0–$1\frac{1}{2}$-in. sand and pebble aggregate for which the percentage of sand varied over a wide range. A fineness modulus of 4.0 gave a ratio of initial tangent modulus to compressive strength

TABLE II.—RATIO OF INITIAL TANGENT MODULUS OF ELASTICITY TO COMPRESSIVE STRENGTH OF CONCRETE.

Mix by Volume.	Water-Ratio to Volume of Cement for Different Relative Consistencies.					Ratio of Initial Tangent Modulus of Elasticity to Compressive Strength of Concrete for Different Relative Consistencies.				
	0.90	1.00	1.10	1.25	1.50	0.90	1.00	1.10	1.25	1.50
1 : 7	0.97	1.08	1.19	1.35	1.62	2300	3060	3000	3700	4060
1 : 5	0.79	0.88	0.96	1.09	1.31	1520	1610	2300	3120	2500
1 : 4	0.70	0.77	0.85	0.96	1.16	800	1600	1690	2600	3270
1 : 3	0.60	0.67	0.74	0.84	1.00	1120	1350	1420	1660	2580
1 : 2	0.51	0.57	0.62	0.71	0.85	1000	1060	1310	1710	2180
1 : 1	0.42	0.46	0.51	0.58	0.70	840	910	780	1220	1140
1 : $\frac{1}{3}$	0.35	0.39	0.43	0.49	0.59	720	890	790	610	1060
Average	.....	.....	.....	.....	.....	1180	1430	1610	2090	2550

of 2300, a fineness modulus 5.0 gave 2050, 5.5 gave 1490, 5.75 gave 1610, 6.0 gave 1880, 6.25 gave 1700 and 6.50 gave 1990. A low fineness modulus corresponds to a high percentage of sand, and a high fineness modulus to a low percentage of sand.

It will be noted from these data that the ratio is higher for the wetter consistencies, leaner mixtures and lower fineness moduli (higher percentage of sand)—in other words the ratio is higher for the weaker concrete. A little study will show that this is in accordance with the information brought out by Figs. 3 and 4, since the modulus of elasticity increases with strength less rapidly for the stronger concrete.

As a point of information the writer would like to know from what tests reported in this paper Mr. Williams forms his conclusions that:

1. "For ordinary working loads, and up to 50 to 70 per cent of the ultimate strength of the concrete, 95 per cent of the value for modulus of elasticity obtained by dividing the unit stress Mr. Walker.

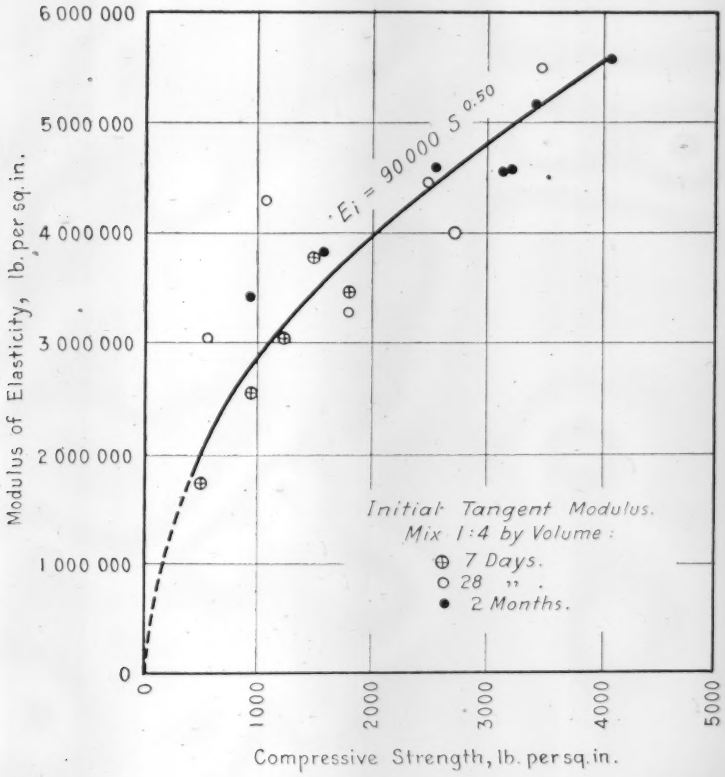


FIG. 4.—Relation of Modulus of Elasticity to Strength of Concrete.

Compression tests of 6 by 12-in. cylinders.
Sand and pebble aggregate graded 0–1½ in.
Each value is the average of 24 tests from six different mixing times.

by the unit deformation for that load will represent the true modulus with sufficient accuracy."

2. "The value of the modulus of elasticity of concrete in a structure is probably slightly greater than that determined by tests of cylindrical specimens."

Mr. Slater.

MR. W. A. SLATER.—If I were to criticize this paper, it would be because the statement of the conclusions has been rather too general. I think on the whole, with possibly one exception, the conclusions are pretty well justified but I believe the wording should be such as will limit these conclusions to the tests which are reported in the paper. I think, however, there is danger of losing perspective in the study of the modulus of elasticity of concrete. This applies not only to the work done in this investigation, but also that which Mr. Walker has referred to. What we are interested in is not wholly what happens to the beam at working loads and below; we are interested just as much in what happens at loads above the working load, so we can have a basis for judging of the factor of safety. When Mr. Williams uses a straight line relation and neglects what happens at loads above those at which the straight line fits the stress-deformation curve and when Mr. Walker uses an exponential curve and neglects what happens after the exponential curve and stress-deformation curve leave each other, I think they both fall into the same error.

To bring out something of the relation between the richness of the mix and the ratio of the modulus of elasticity to the compressive strength I have shown in Fig. 5 the values which Mr. Williams obtained and also some values from Mr. Walker's paper. The ratios of the modulus of elasticity to the compressive strength are plotted as ordinates and the compressive strength in the concrete as abscissæ. For each of the angles in the curve which represents the results of Williams' tests there are two points so close together that you will probably not be able to see that there are two points from where you sit. That is merely a demonstration of the fact which Mr. Williams pointed out, that for the extreme ranges of moisture in the concrete, the ratio of the modulus of elasticity to the compressive strength was the same if the richness of the mix was the same. The error which I believe Mr. Williams fell into was in stating his conclusion in such a way that it seems to apply to a much wider range of conditions than those which he had tested. In looking over Mr. Walker's paper I find that if he would confine his consideration to a variation in the amount of mixing water in the concrete which is within the range of Mr. Williams' tests he would find

approximately the same relation holding which Mr. Williams points out. The values from Mr. Walker's paper[1] show in a fairly consistent way, agreement with the values which Mr. Williams has shown. The values used here are all reported to have had a consistency of 1.10. A study of Table IV indicates

Mr. Slater.

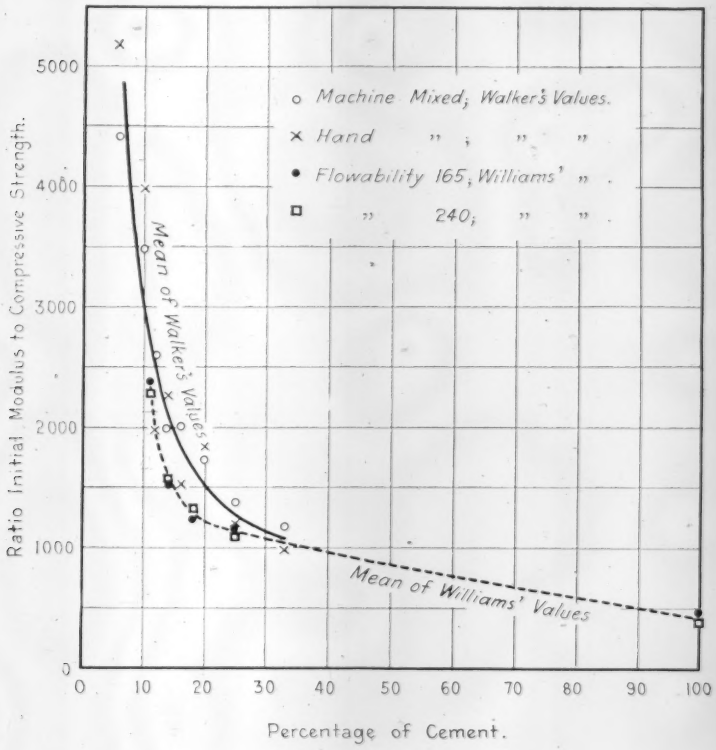


FIG. 5.

The percentage of cement as used in this diagram is based upon the arbitrary mixes stated by Walker and Williams. For example, a mixture reported as 1:6 or as 1:2:4 is used in this diagram as having 16⅔ per cent of cement.

that for consistencies of 1.10 or less the ratio of modulus of elasticity to compressive strength was nearly constant.

There is a further interest in this kind of a curve which is different from that which has been pointed out. It has been

[1] Tables VII and VIII, Stanton Walker, "Modulus of Elasticity of Concrete," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

Mr. Slater. customary to plot the modulus of elasticity as ordinates and the compressive strength as abscissæ and to try to find out the relation between these two functions. Apparently for any compressive strength there may be a great many relations. For a mix which has only 6 per cent of cement we find a very high ratio between the modulus of elasticity and the compressive strength; for a very rich concrete we find a very low ratio. So, instead of being able to plot one curve which will show the relation between modulus of elasticity and compressive strength, a family of curves probably would be found which would depend on some other functions than the strength, perhaps the percentage of cement, perhaps on other things. In this particular curve it looks as though it were closely related to the percentage of cement.

As shown in a recent paper[1] based on tests made at St. Louis by the U. S. Geological Survey a number of years ago, it was found that for a very lean concrete a very much greater compressive strength was developed in a beam than in a cylinder; for very rich concrete, about the same compressive strength was developed in the beam as in a cylinder. By the term compressive strength in the beam is meant the compressive stress calculated by the parabolic formula for the maximum load provided that failure was by crushing of the concrete. The assumption that the same relation between the modulus of elasticity, the compressive strength, and the richness of the mixture as is pointed out by Mr. Williams, existed in the beams would be sufficient to account for the greater strength (in proportion to the cylinder strength) in the beams of lean than in those of rich concrete. Sufficient study has not been given to this matter to warrant any more detailed statement than this at the present time.

Mr. Walker showed on the screen some test results by Mr. Lagaard. I think that there is one feature in the study of that diagram that he overlooked, that at the lower portion of those diagrams he did not find the little curve which gives rise to the exponential form of equation. When Mr. Walker first proposed the exponential formula I thought that that curve at the bottom was an instrumental error. I had noticed it in the cylinder stress-

[1] W. A. Slater and R. R. Zipprodt, "Compressive Strength of Concrete in Flexure," *Proceedings*, Amer. Conc. Inst., Vol. XVI, p. 120 (1920).

deformation curves, but had paid little attention to it because I thought it was due to error of setting the instrument or reading it or something of that kind, but since Mr. Walker has called attention to it, I have observed it in a good many cases; in fact it could have been observed in the curves Mr. Williams prepared for this paper. It is there in many instances but I believe too much significance has been attached to it, as that is the only thing I see in the stress-deformation relation that justifies anything like an exponential formula. **Mr. Slater.**

MR. D. A. ABRAMS.—In Fig. 2 in Mr. Williams' paper there are two curves on the right hand side, one of which is slightly concave upward and the other slightly concave downward. I should like to ask if it is not possible that the upward curvature of curve 40 *b* (later application of load) may be explained by the fact that the load was reapplied shortly after it had been released, before the beam had time to fully recover? Concrete is elastic and subject to the same laws that govern other materials, and a certain time must elapse before it comes back to its original length. **Mr. Abrams.**

MR. W. A. SLATER.—I think it is entirely possible that it might. However, there are a number of other curves given which did not show the upward curvature. I do not know what the significance of that is. I pointed it out because Mr. Williams stated in the paper that it persisted throughout a number of applications of the load. **Mr. Slater.**

Mr. A. T. GOLDBECK.—I have been wondering what the practical significance of this slight difference in the shape of the curves obtained by Mr. Walker and those of Mr. Williams is. In one case a straight-line stress-deformation curve is obtained and in the other case this line is a curve having very slight curvature. We know that concrete "flows" or is permanently deformed when subjected to continuous stresses, even when well within the ordinary working stresses, and I cannot see that this slight difference in shape of curve has any practical significance on this account. **Mr. Goldbeck.**

MR. W. A. SLATER.—Mr. Walker, in connection with his paper on the modulus of elasticity, developed a beam analysis in which he applied the curve which he had developed. A study of the results of the analysis indicates that with the use of the **Mr. Slater.**

Mr. Slater. exponential formula and the same working stresses the calculated working load would be about three to five per cent more than with the use of the straight line formula.

Mr. Talbot. MR. A. N. TALBOT.—I should like to ask the author of the paper the significance of the value of the modulus of elasticity as determined from these repetitive loadings? I assume from what has been said that the value is calculated from the net strain and not from the total strain obtained by the use of a reading before the application of the first load. If it is expected that such a value may be used in determining the stresses in reinforced concrete, it seems to me that objection may be made. For example, in a column reinforced with longitudinal rods, after a repetition of load there is a shortening of the column left after the removal of the load, and it would seem then that there must be a residual stress in the steel and that calculations should take that into account, because the determination of the amount of stress in the steel is desired as well as the stress in the concrete. Similarly in the case of the beam under flexure, the total deformation is a matter which should be taken into consideration, and the net deformation will not give the true significance of the action of the combination of concrete and steel.

Mr. Williams. MR. G. M. WILLIAMS (*Author's closure by letter*).—The intent of the investigation summarized in this paper was to determine the true stress-deformation relation up to and beyond usual working loads for Potomac River sand and gravel concrete, for wide variations in cement content and for the range of consistencies commonly employed in practice.

Mr. Walker's discussion, as understood by the writer, confines itself to the stress-deformation relation obtained by a single loading of many specimens. As the writer has pointed out, a curved relation which may be expressed by an equation of the exponential type is sometimes obtained for the first loading, but the straight line relation will be found for later applications of load. The writer believes that no consideration should be given to values found for first application of load, and that the true working relation is that obtained with later applications. Concrete in structures is exposed to either constant or variable loadings, and within the limits of safe working stresses the straight line relation is the true relation. The same conclusion

Mr. Williams.

may be drawn from the many tests made in the laboratory of the U. S. Geological Survey at St. Louis several years ago. It seems possible to the writer that some of the results obtained by Mr. Walker for first loadings may be due to the type of instrument which he has used, since the single dial instrument gives no indication of unequal distribution of stress. The writer has found the three dial type to be very sensitive in this respect, and in some instances where every care was employed to surface the ends of the specimen and properly adjust it in the machine, stresses were unevenly distributed over the cross-section of the specimen, necessitating removal of load and shifting of the position of the specimen.

The slight differences obtained for modulus of elasticity of concrete in wet and dry condition has been noted for specimens which were two years old and again when eight years old, so that it is not understood how age can greatly affect the results obtained at any single period. Furthermore, in the tests reported, all first loadings were made on saturated specimens, just removed from storage, and the values for modulus of elasticity so obtained are practically the same as those found several weeks later after the specimens had dried in air. It should be noted that increase due to greater age, plus any expected increase due to dry condition, did not result in higher values being obtained. Tests made on specimens several years old meet with Mr. Walker's requirement that the period required for drying should be only a small percentage of the age at the time of the tests. The results show, however, that a few days difference in age after the 28-day storage period has very slight effect on the modulus of elasticity.

The consistencies employed which Mr. Walker believes were limited to a very narrow range, varied as widely as need ever be employed in practice. No predetermined quantity of water was used, but an attempt was made to obtain as dry a concrete as could well be molded under laboratory conditions, and as a wet concrete as should ever be permitted on any work. A concrete drier than flowability 165 would be unplaceable in ordinary work, and a flowability of 240 approaches a sloppy segregating mix.

The conclusion drawn for relation of modulus of elasticity to compressive strength gives proper consideration to possibilities

Mr. Williams. of other relations being found when one or more factors are varied since it states that the relation is true for the "given . . . grading of aggregate." This conclusion was carefully worded so as to apply only to the materials and conditions of test employed in this investigation, and is also incidental since the primary object was to determine the true stress-deformation relation within practical working limits.

A value of 95 per cent of the modulus obtained by dividing unit stress by unit deformation for any loading up to 50 to 70 per cent of ultimate strength was suggested for such values as might be calculated without plotting the stress-deformation curve. In this calculation it is assumed that the curve passes through the origin, but a plot will often show the curve a short distance to the left of the origin.

Continuous application of load with later releases and applications consistently gave slightly higher values for E than were obtained during the first few loadings. Since concrete in a structure is constantly stressed it seems reasonable to assume that the modulus is likewise slightly increased.

With reference to Mr. Slater's discussion, the purpose of this paper was to determine the stress-deformation relation for concrete up to and beyond the usual working loads, but below the elastic limit. For this reason no data were included to show the relation for loadings beyond the elastic limit, although such data were obtained for those specimens tested to the ultimate. It was intended to point out and emphasize the true relation for concrete as used in practice. The attempt to complicate the relation and apply an exponential equation to this relation for working loads cannot be justified by any test data which the writer has obtained and the aim has been to emphasize that the simple straight line relation is the true relation for such loadings. The writer fully agrees that knowledge of the stress-deformation relation just previous to failure is necessary for determination of the factor of safety and studies of ultimate strengths, but the inclusion of such data would only have been confusing in this particular case. Such data as may be obtained for higher loadings, however, will in no way alter the relation as found and reported for safe working stresses.

As Mr. Talbot points out, total deformation of the concrete

must be taken into consideration in studies of reinforced concrete. This total deformation due to repeated and continuous applications of loads acts in a manner similar to the shortening of a concrete member due to drying out of the concrete, and the effect is similar to temperature changes when the coefficients for concrete and steel are unequal. No attempt has been made to point out what effect this cumulative deformation may have in reinforced concrete structures, but merely to indicate some fundamental relations between stress and deformation. In this connection it should be noted that the modulus remains constant or increases slightly as this total deformation increases within the limits of working stresses. Mr. Williams.

The writer believes that the uncertainty existing as to the true stress-deformation relations for concrete is due in part to the use of instruments which have not permitted the detection of unequal stresses over the cross-section of the test piece, but primarily to exaggeration of the importance of the slight curvature for small loads found at first loading after adjusting the instruments, and which has no importance or significance in the design of reinforced concrete structures. Persistence in study of this relation for the first loading of a specimen, when further tests comparable with the treatment of a concrete member in practice will clearly show a simpler relation, can only be attributed to a tendency to disregard the practical application of the results of such a test, and force of habit which causes later investigators to blindly repeat the inadequate methods and processes employed when a test is first introduced.

IMPACT TEST ON CONCRETE TO REGULATE COARSE AND FINE AGGREGATE QUALITIES AND MIXES FOR HIGHWAYS.

By H. S. Mattimore.

There are varied opinions of investigators on highway problems as to the required qualities of coarse and fine aggregate for use in concrete surfacing for highways. It is true that these are specified by most departments building this type of highway, but these specifications are mainly followed as a good protective measure for quality rather than being based on known data.

In order to obtain some accurate data on these problems, the Pennsylvania Highway Department constructed a service test road with departmental forces. The State has a large variety of different qualities of both fine and coarse aggregate and definite knowledge of how these materials could be utilized to the best advantage in permanent type highways was essential in order economically to carry on the large road-building program now under way.

On the part of the road finished during 1919, thirteen sections of concrete were constructed, varying from 200 to 300 ft. in length. Different qualities of coarse and fine aggregate were mixed in several different proportions, and in order to test different methods of finishing, where the proportions used were favorable, one-half of the section was finished by roller, belt, and hand floating, while on the other half a finishing machine was used. It was noted at the time that the mixes containing a large amount of coarse aggregate such as a 1 : 2 : 5 and a 1 : $1\frac{1}{2}$: 4 could not be properly finished by other methods than the machine.

During the course of construction, test specimens were cast in the field. At each section or change of mix, four 6 by 12-in. cylinders were molded for a compression test and two 6 by 6-in. cylinder for the impact wear test.

The machine for the impact wear test, as illustrated in Fig. 1, consists of a striking head mounted on a frame. This head, illustrated in Fig. 2, was originally fitted with nine striking points designed for a 6-in. cube test specimen, but when modified for testing cylinders 6 in. in diameter, eight points were found to work more satisfactorily. The striking head is

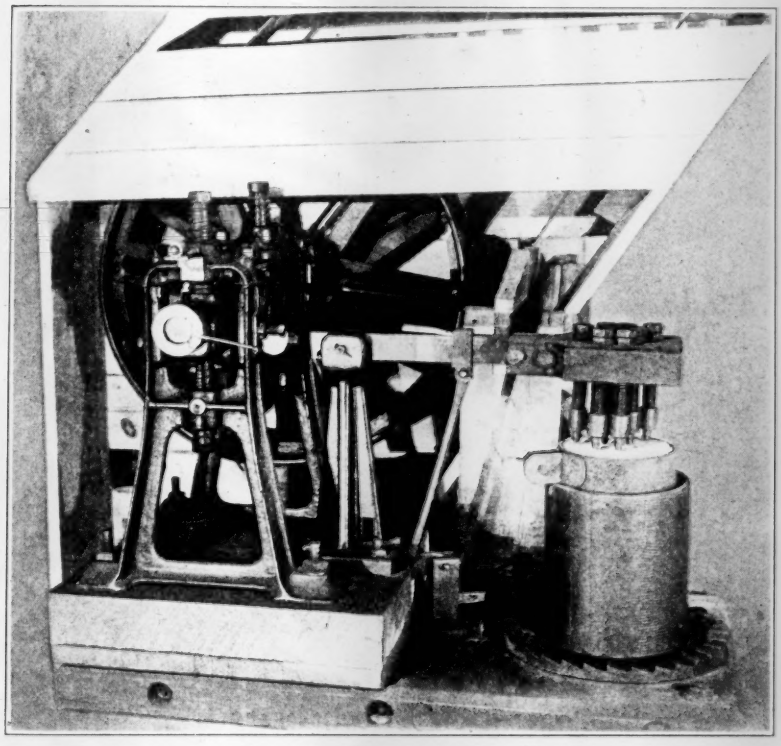


FIG. 1.—Machine for Impact Wear Test.

raised and released by a cam attached to the shaft at the end of the handle. The springs fitted to the points give $\frac{1}{2}$-in. play, thus allowing for wear of the matrix between the aggregate. The striking points consist of non-slip horse calks having a radius of curvature of 0.2 in., which can readily be replaced. The specimen holder can be changed to fit cylinders from 6 to 12 in. in height.

The specimen rests on a sand cushion several inches in depth. The holder is revolved by means of a dog attachment to the striking-head handle, thereby allowing successive blows to be delivered at different parts of the surface. The effective blow is 29 lb. dropping

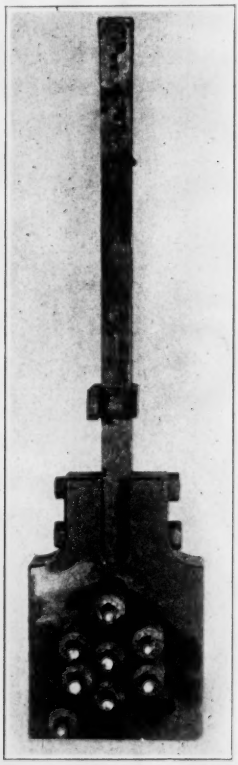


FIG. 2.—Striking Head of Impact Machine.

4 in. at the rate of 90 r.p.m. The test consists of 5000 blows. The impact coefficient is computed by the following formula:

$$\text{Impact Coefficient} = \frac{\text{Loss of weight in grams}}{170} \times 100.$$

The constant 170 was arrived at by studying the action of various aggregate combinations and mixes in several hundred miles of concrete highways under several years of traffic. A dupli-

cate of these aggregate combinations and mixes were molded in specimens and subjected to test. A loss of 170 g. was found to be a good normal condition and this was established as a standard value.

In order to test the effect of manipulation and different

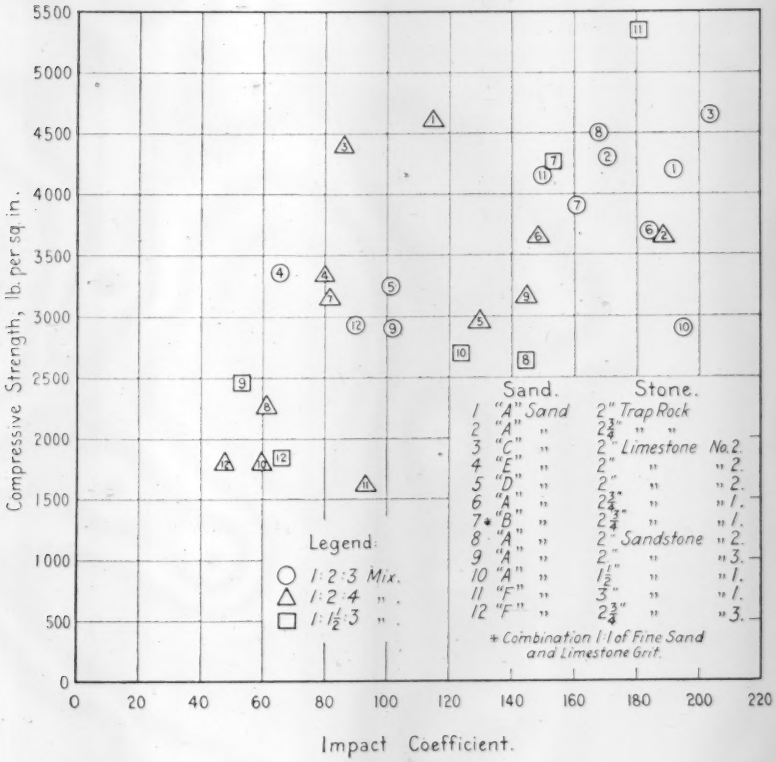

Compressive Strength, lb. per sq. in.
Impact Coefficient.
Legend:
1:2:3 Mix.
1:2:4 " .
1:1½:3 " .
Sand. Stone.
1 "A" Sand 2" Trap Rock
2 "A" " 2¾" " "
3 "C" " 2" Limestone No.2.
4 "E" " 2" " "2.
5 "D" " 2" " "2.
6 "A" " 2¾" " "1.
7* "B" " 2¾" " "1.
8 "A" " 2" Sandstone "2.
9 "A" " 2" " "3.
10 "A" " 1½" " "1.
11 "F" " 3" " "1.
12 "F" " 2¾" " "3.
* Combination 1:1 of Fine Sand and Limestone Grit.

FIG. 3.—Showing Relation between Impact Coefficient and Compressive Strength of Molded Specimens.

methods of finishing, cores were drilled out of the finished concrete surface about three months after it was placed. The cores averaged $6\frac{1}{4}$ in. in diameter and had a depth equal to the road section. The maximum variation in diameter on 43 cores was found to be about $\frac{1}{8}$ in. These specimens were subjected to impact wear test and the results are plotted in Figs. 4 and 5.

Each test result on all figures is given a number which identifies it with the section on the highway from which it was cast or drilled. The different mixes are designated by symbols, so individual results can readily be traced through the different figures.

Fig. 3 is a plotting of compression and impact-coefficient test values on specimens molded in the field during construction.

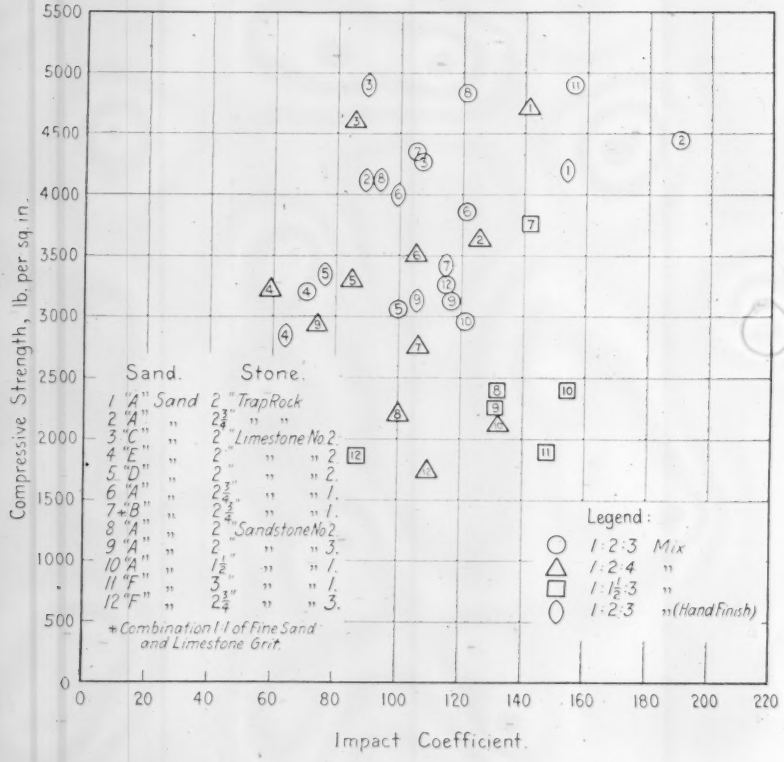

Compressive Strength, lb. per sq. in.
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0 20 40 60 80 100 120 140 160 180 200 220
Impact Coefficient.
Sand. Stone.
1 "A" Sand 2 " Trap Rock
2 "A" " 2¾ " " "
3 "C" " 2 " Limestone No. 2.
4 "E" " 2 " " " 2.
5 "D" " 2 " " " 2.
6 "A" " 2¾ " " " 1.
7 "B" " 2¾ " " " 1.
8 "A" " 2 " Sandstone No. 2
9 "A" " 2 " " " 3.
10 "A" " 1½ " " " 1.
11 "F" " 3 " " " 1.
12 "F" " 2¾ " " " 3.
+ Combination 1 1 of Fine Sand and Limestone Grit.
Legend:
1:2:3 Mix
1:2:4 "
1:1½:3 "
1:2:3 " (Hand Finish)

FIG. 4.—Showing Impact Coefficient-Compressive Strength Relation. Impact Test on Drilled Cores, Compression Test on Molded Specimens.

The aggregates used in all the specimens are tabulated on this figure and the data given pertain to all other figures. This figure illustrates that although a general relation might exist between compression and impact, the individual results varied

to such an extent that compression could not be used as a guide to indicate resistance to impact wear.

Fig. 4 is a plotting of compression and impact coefficient as in Fig. 3. In this illustration the compression values are the

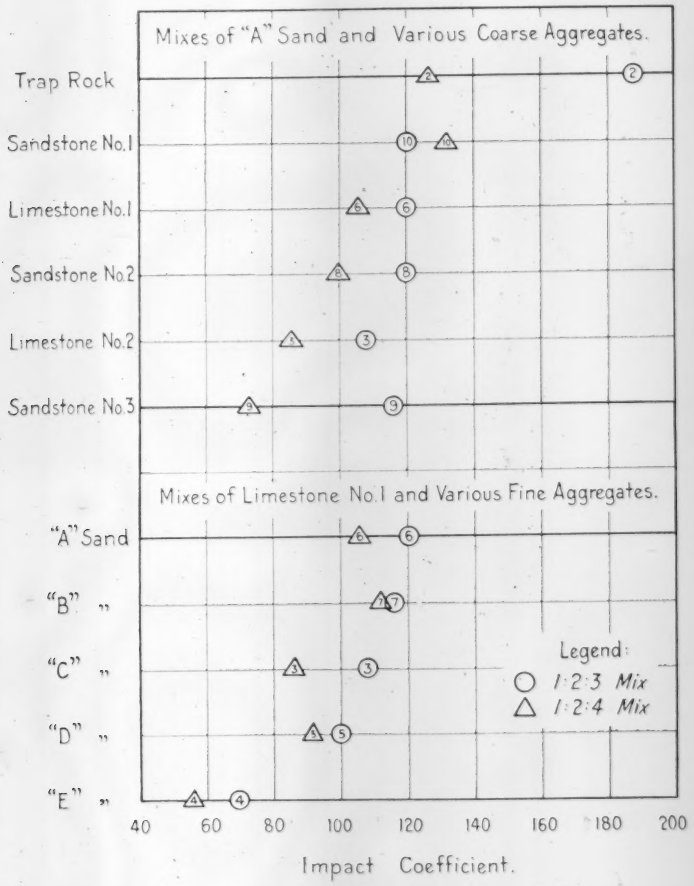
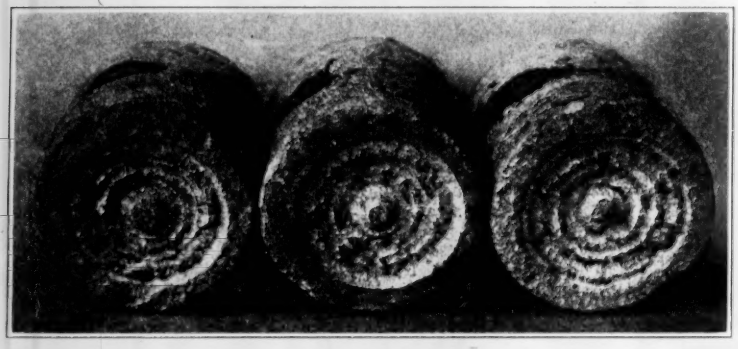


FIG. 5.—Effect of Impact on Different Mixes, Varying First the Coarse and then the Fine Aggregate.

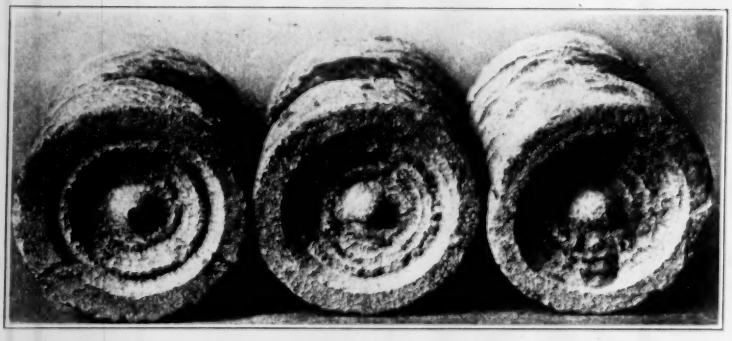
same as in Fig. 3, but the impact coefficient is a result of tests on specimens drilled from the road surface. These drilled cores have not been subjected to compression tests as yet, as it is desired to keep them intact for other tests.

Fig. 5 is made up by plotting impact coefficient values taken from Fig. 4. It illustrates, first, the effect of impact when using one sand with different coarse aggregates in 1 : 2 : 3 and 1 : 2 : 4 mixes. Second, it shows the effect of impact in the



2 (1 : 2 : 3) 2 (1 : 2 : 4) 3 (1 : 2 : 4)

FIG. 6.—Cores Drilled from Road. After Impact Test.



6 (1 : 2 : 3) 5 (1 : 2 : 4) 4 (1 : 2 : 4)

FIG. 7.—Cores Drilled from Road. After Impact Test.

same mixes when using limestone as a constant with different fine aggregates. A study of this figure illustrates the uniformity of a 1 : 2 : 3 mix when compared with the 1 : 2 : 4.

Fig. 5 also illustrates the great difference in test values

TABLE I.—PROPERTIES OF AGGREGATES. (SEE FIGS. 3 AND 4).

STONE TESTS.

Properties.	Trap Rock.	Sandstone No. 1.	Limestone No. 1.	Sandstone No. 2.	Limestone No. 2.	Sandstone No. 3.
Specific gravity	2.97	2.52	2.77	2.45	2.75	2.34
Weight, lb. per cu. ft.	185.30	157.20	172.90	152.90	171.70	146.00
Absorption, lb. per cu. ft.	0.12	1.25	0.43	1.52	0.10	3.60
Percentage of wear	2.10	2.40	3.60	3.40	4.30	8.20
French coefficient of wear	19.00	16.60	11.10	11.70	9.30	4.80
Crushing strength, lb. per sq. in. (cylinders 1 in. diameter)	24.560	23 348	17 642	25 528	18 956	10 894
Grading:						
Passing ⅛-in. screen, per cent	0.1	1.5	0.2	3.0	0.3	4.9
" ¼-in. " "	0.1	0.9	0.2	1.9	0.3	1.3
" ½-in. " "	0.6	7.7	1.6	6.0	0.3	8.2
" ¾-in. " "	7.2	27.1	6.9	14.2	3.6	22.3
" 1-in. " "	14.6	26.1	14.0	20.7	1.33	22.9
" 1¼-in. " "	12.7	21.6	21.7	22.5	26.3	21.8
" 1½-in. " "	8.7	14.2	16.1	14.6	28.7	13.5
" 2-in. " "	18.0	0.9	24.3	17.1	27.2	5.1
" 2½-in. " "	13.8	....	13.0	....	....	....
" 3-in. " "	19.2	....	2.0	....	....	....
Retained on 3-in. screen	5.0	....	....	....	....	....
Totals of percentage	100.0	100.0	100.0	100.0	100.0	100.0

SAND TESTS.

Sand	A	B[1]	C	D	E	F
Grading:						
Passing 200-mesh sieve, per cent	0.5	2.5	0.5	5.3	16.8	0.3
" 100-mesh " "	0.9	0.8	0.4	5.5	4.2	0.9
" 80-mesh " "	1.6	0.6	0.6	3.1	1.3	0.6
" 50-mesh " "	13.2	2.1	10.2	18.0	5.9	4.2
" 40-mesh " "	11.1	14.3	13.1	14.8	4.3	8.3
" 30-mesh " "	20.7	29.7	23.7	18.0	9.5	18.2
" 20-mesh " "	14.7	10.2	15.5	6.8	10.7	25.7
" 10-mesh " "	17.0	13.0	17.3	7.9	22.0	40.6
" ⅛-in. " "	5.8	6.8	3.9	5.8	6.9	1.2
" ¼-in. " "	14.5	20.0	14.8	15.3	18.4	0.0
Totals of percentages	100.0	100.0	100.0	100.0	100.0	100.0
Retained on ¼-in. sieve, per cent	5.1	16.0	3.9	5.4	3.8	0.0
Tensile Strength ratio:						
7 Days	114.9	129.0	106.2	89.1	87.2	106.5
28 Days	106.1	112.2	118.8	107.1	95.1	104.0

[1] Combination 1 : 1 of fine sand and limestone grit.

between these two mixes when different coarse aggregates are used with the same fine aggregate; therefore, under such conditions a 1 : 2 : 3 mix is recommended. Where different fine aggregates are used with the same coarse aggregates, the test values show only a slight variation and either mix might be used

Table I is a tabulation of the grading and quality tests of both fine and coarse aggregates used in the various specimens. This table should be consulted in conjunction with the tabula-

9 (1 : 1½ : 3) 9 (1 : 2 : 4)

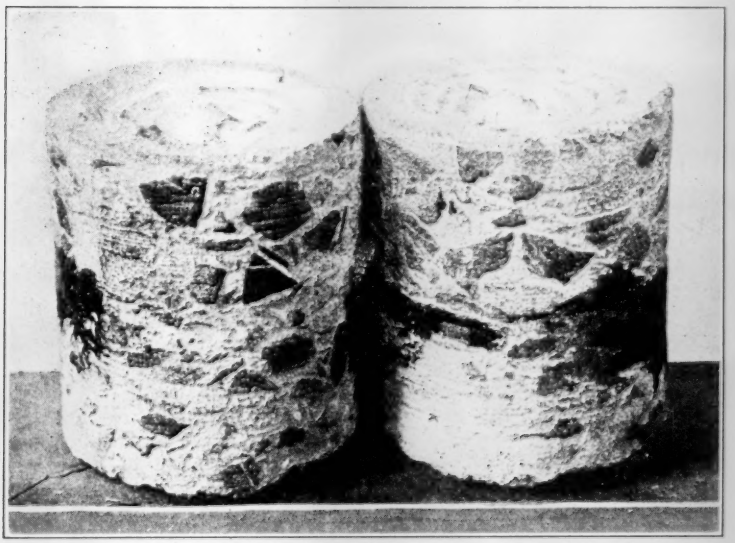
FIG. 8.—Cores Drilled from Road. After Impact Test.

tion on Figs. 3 and 4. By means of specimen numbers and the two tabulations, a complete quality test of the concrete is available.

Figs. 6, 7 and 8 are illustrations of cores drilled from the road showing effect of impact. The individual cores have the same number as the specimens on the plots and can be identified from the tabulation on Fig. 4.

Fig. 9 is an illustration of two cores drilled from the road showing the depth of the cores.

Although the test specimens recorded in this data are limited in number, I believe it is justifiable to draw the conclusion arrived at from the following standpoint. First, the test specimens represent concrete mixed under excellent control in actual practice. Second, the drilled cores give an opportunity to judge the effect of manipulation and different finishing methods on road surfaces, factors on which there is very little if any known data at the present time.



4 (1 : 2 : 3) 4 (1 : 2 : 3)

FIG. 9.—Cores Drilled from Road. After Impact Test.

The definite conclusions based on a study of these data are:

1. The qualities of both coarse and fine aggregate influence both compression and impact wear test.

2. The quality of the fine aggregate has a greater effect on the impact wear test than that of the coarse aggregate.

3. A 1 : 2 : 3 mix gives more uniform results in impact wear test than a mix with a larger proportion of coarse aggregate.

4. The 1 : 2 : 4 and the 1 : $1\frac{1}{2}$: 3 mixes are affected to a

greater extent by the qualities of the coarse aggregate than a 1 : 2 : 3 mix.

5. Where an excellent quality of fine aggregate is to be used with a medium quality of coarse aggregate a 1 : 2 : 3 mix should be used.

6. Where an excellent quality of coarse aggregate is to be used with a medium quality of fine aggregate, there is very little difference in impact wear between a 1 : 2 : 3 and a 1 : 2 : 4 mix, so it may be economical to use the latter.

7. More uniform results were obtained under impact wear test on specimens drilled from the road, than on the molded specimens.

8. There is no direct relation observed between impact wear test and compression.

9. Machine-finished concrete gives more uniform results in impact wear test than hand-finished concrete, although some specimens of the latter give higher values.

DISCUSSION.

MR. J. H. LIBBERTON.—I should like to ask Mr. Mattimore if the samples he calls hand molded were finished in the usual manner with the trowel? Were the processes of pavement construction imitated as nearly as possible? **Mr. Libberton.**

MR. H. S. MATTIMORE.—Yes, the samples were all finished by the laboratory operators by "floating" with a wooden float and trowel. We also tried at the same time to sink some specimens down to the road surface and have the mechanical finisher go over them, but that did not work out successfully. **Mr. Mattimore.**

MR. LIBBERTON.—Would it not be better, in making laboratory specimens where it is essential that you know the proportions, to make up larger specimens and drill them out with the drilling machine the same as samples taken from the road? **Mr. Libberton.**

MR. MATTIMORE.—I believe you could do that if you had to, but as we had the machine on the road it was not necessary. **Mr. Mattimore.**

THE CHAIRMAN (PAST-PRESIDENT A. N. TALBOT).—Reference is made in the description of the machine to springs. In what way are there springs in the machine? **The Chairman.**

MR. MATTIMORE.—The springs are around the rod to which the points are attached, so that the blow is transmitted through these springs. **Mr. Mattimore.**

THE CHAIRMAN.—Are the springs stiff? **The Chairman.**

MR. MATTIMORE.—Yes, they are medium stiff springs; it takes quite a pressure with the hand to play them. **Mr. Mattimore.**

THE STANDARD DEVAL ABRASION TEST FOR ROCK.

By F. H. Jackson.

In 1917, the author presented a paper before the Society on the "Effect of Controllable Variables on the Toughness Test for Rock."[1] Partly as a result of the work outlined in that paper the old standard method of the Society was revised to take care of a number of details in connection with the conduct of the test which had not been covered adequately. The present paper gives the results of a somewhat similar study of the standard Deval abrasion test, the revision of which is now being considered by Committee D-4 on Road Materials.

This test is probably the best known and most widely used of any of the methods which have been developed for testing the quality of road-building rock. It has been in continuous use in this country for over 20 years and, in general, has been considered satisfactory for the purpose for which it was designed: that is, to measure the relative resistance of rock to wear or abrasion. In spite of this fact, however, it must be confessed that the method is weak in at least two particulars. In the first place, experiments made recently have indicated the possibility of a considerable error in results obtained due to variations in laboratory manipulation. For instance, Mattimore, in 1917, reported[2] a series of results in which ten tests on a sample of dolomite made in the same laboratory and by the same operator but on different days showed a maximum variation in percentage of wear of 0.9 per cent. A corresponding series of tests on syenite showed a maximum variation of 1.3 per cent. In the same year Reinecke and Clark[3] in a paper before the Society reported a maximum variation of 0.6 per cent on 17 duplicate sets of limestone, and a corresponding maximum variation of 0.3 per cent on 7 duplicate sets of igneous rock.

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVII, Part II, p. 571 (1917).
[2] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 415 (1918).
[3] *Ibid.*, p. 398.

In both of the cases cited, care was exercised to insure, as nearly as possible, the use of identical material in all of the check tests. The variations noted are therefore assumed to be due to laboratory manipulation alone.

Results of tests made by the author along the same line are given in Table I. The results shown in the table were

TABLE I.—COMPARATIVE RESULTS OF ABRASION TESTS USING STANDARD AND PROPOSED METHODS.

Test No.	Type of Rock.	Percentage of Wear by Standard Method.					Percentage of Wear by Proposed Method.				
		Individual Results.			Average.	Maximum Deviation.	Individual Results.			Average.	Maximum Deviation.
1	Granite	4.0	4.3	4.6	4.3	0.6	6.0	5.8	5.7	5.9	0.3
2	"	5.0	4.4	4.6	4.7	0.6	6.0	5.9	6.1	6.0	0.2
3	"	3.0	3.3	2.9	3.1	0.4	3.9	4.1	4.0	4.0	0.3
4	Trap	2.0	2.7	2.5	2.4	0.7	3.0	3.2	3.0	3.1	0.2
5	"	2.9	2.5	2.6	2.7	0.4	4.0	4.1	4.3	4.2	0.3
6	Limestone	5.9	6.3	6.8	6.3	0.9	12.0	12.3	12.4	12.2	0.4
7	"	9.3	10.8	10.6	10.2	1.5	29.4	29.0	29.6	29.4	0.6
8	Sandstone	5.8	6.7	7.0	6.5	1.2	13.1	13.0	13.3	13.2	0.3
Average						0.8	Average				0.3

obtained from time to time in the course of the routine work of the laboratory of the Bureau of Public Roads and extended over a period of a year or more. No effort was made to specially prepare any of the samples. They were, however, all prepared by the same operator—an experienced man who has been engaged in this work for the past 18 years. These results indicate clearly the degree of accuracy which may be expected in a given laboratory and under average normal conditions. It will be noted that the average maximum deviation for the four types examined amounts to approximately 0.8 per cent. This would correspond, in the case of granite, trap, or other hard rock having, for instance, an average percentage of wear of 3, to a possible variation of from 12 to 16 in French coefficient of wear, or four points. This is rather a serious error and calls for a greater tolerance in interpreting the results of tests than we have been in the habit of considering necessary. The principal reason for the discrepancies noted is the practical impossibility of securing by the ordinary method of hand-breaking a test sample consisting of

FIG. 1.—Forcing Press Used for Preparing Samples for the Abrasion Test.

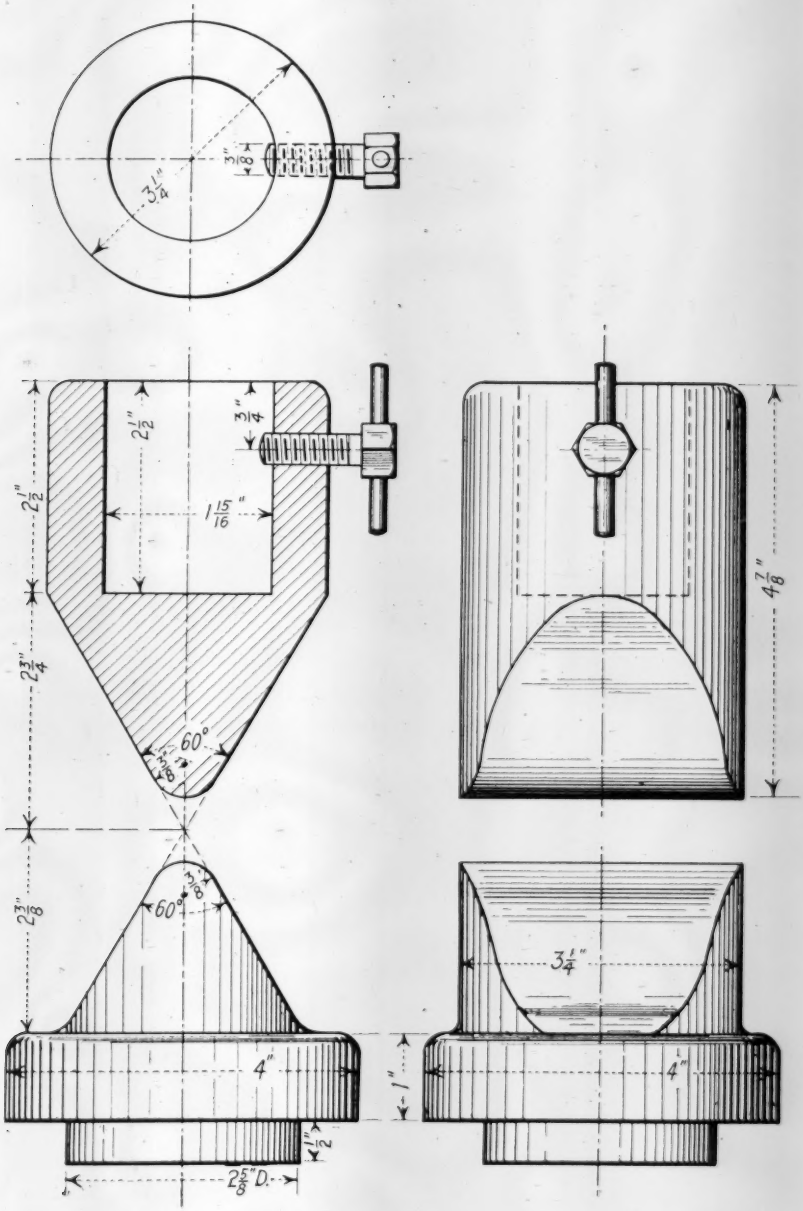


FIG. 2.—Knife Edges Used on Machine for Preparation of Samples for Abrasion Test.

50 pieces all of the same size and shape. It is, of course, obvious that variations in either respect will affect the results obtained, particularly if the stone be unusually soft or brittle. The present standard method requires that a sample of rock for the abrasion test shall weigh within 10 g. of 5000 g. and shall be composed of 50 pieces of freshly-broken stone of as nearly the same size as possible. While no reference is made to the shape of the pieces, the assumption has always been that cubical fragments should be prepared. It has been the author's experience that such a sample is extremely difficult to prepare in the ordinary manner in a reasonable length of time. As a matter of fact, it may be doubted whether it is even approximated in the majority of laboratories.

Appreciating the need of a more rapid as well as accurate method of preparing samples, the laboratory of the Bureau of Public Roads has been for some time experimenting with a forcing press equipped with suitable knife edges for breaking stone. A view of this machine is shown in Fig. 1 and a detail of the knife edges in Fig. 2. It was first used by the laboratory in the preparation of granite paving block samples for test because it was found that the variations obtained when specimens were hand-broken were so great that the results were of little value. It has a capacity of 20,000 lb. which is sufficient to break an ordinary standard-size granite block. By the use of this machine, small cubical fragments of the size desired may be prepared conveniently from practically all types of rock with the exception of some traps and the very highly foliated or laminated varieties, such as gneiss and schist. With these types it is always a question of doing the best possible with the material in hand. A standard sample prepared in the above manner will consist of 50 pieces, approximately cubical in shape, each of which should weigh from 85 to 115 g. Results of tests on samples of different types of rock prepared in this manner and compared to tests on the same materials prepared in the usual way are shown in Table I and will be discussed below.

The Deval test has been criticized also from another point of view. In a paper presented at the 1918 annual meeting of the Society, Scofield[1] called attention to the action of the so-

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, p. 417 (1918).

called "dust cushion" on the inside of the abrasion cylinder. He showed that in eliminating this cushion by removing the dust of abrasion during the test, a much greater range in values could be obtained, especially among the softer rock types. Other investigators working along the same line had independently reached the same conclusion. Indeed, the present method is so obviously wrong in principle it is remarkable that it has not been changed before.

In regard to the elimination of this "dust cushion" the author sees no better way than to simply mill a series of longitudinal slots in the standard abrasion cylinder through which the dust may escape as fast as it is formed. Fig. 3 shows the arrangement of the slots which has been adopted in the Bureau of Public Roads laboratory. They are $1\frac{1}{2}$ in. apart, center to center, and $\frac{1}{16}$ in. wide. A cylinder slotted in approximately the manner shown in the figure has been in use in the laboratory for a number of years. The exact spacing or length of the slots, however, apparently makes very little difference in the actual results obtained, provided there are a sufficient number of openings to permit all of the dust to escape.

Several other suggestions in the way of improving this test, such as the use of small shot as an abrasive agent, a graded instead of a one-size sample, etc., have been offered from time to time. Some of these will be briefly discussed in the conclusions to this paper.

DISCUSSION OF RESULTS OBTAINED.

The work covered in the following discussion was carried out, therefore, with two primary objects in view:

1. To determine how variations in the results of tests due to laboratory manipulation may be reduced;

2. To determine the comparative range in values obtained with and without the "dust cushion."

The results of a number of tests made on samples prepared by machine and tested in the slotted abrasion cylinder are given in Table I, and may be compared to the values obtained in the ordinary manner and to which reference has already been made. It will be noted that the average maximum deviation of 0.8 per cent observed with the standard method has been reduced

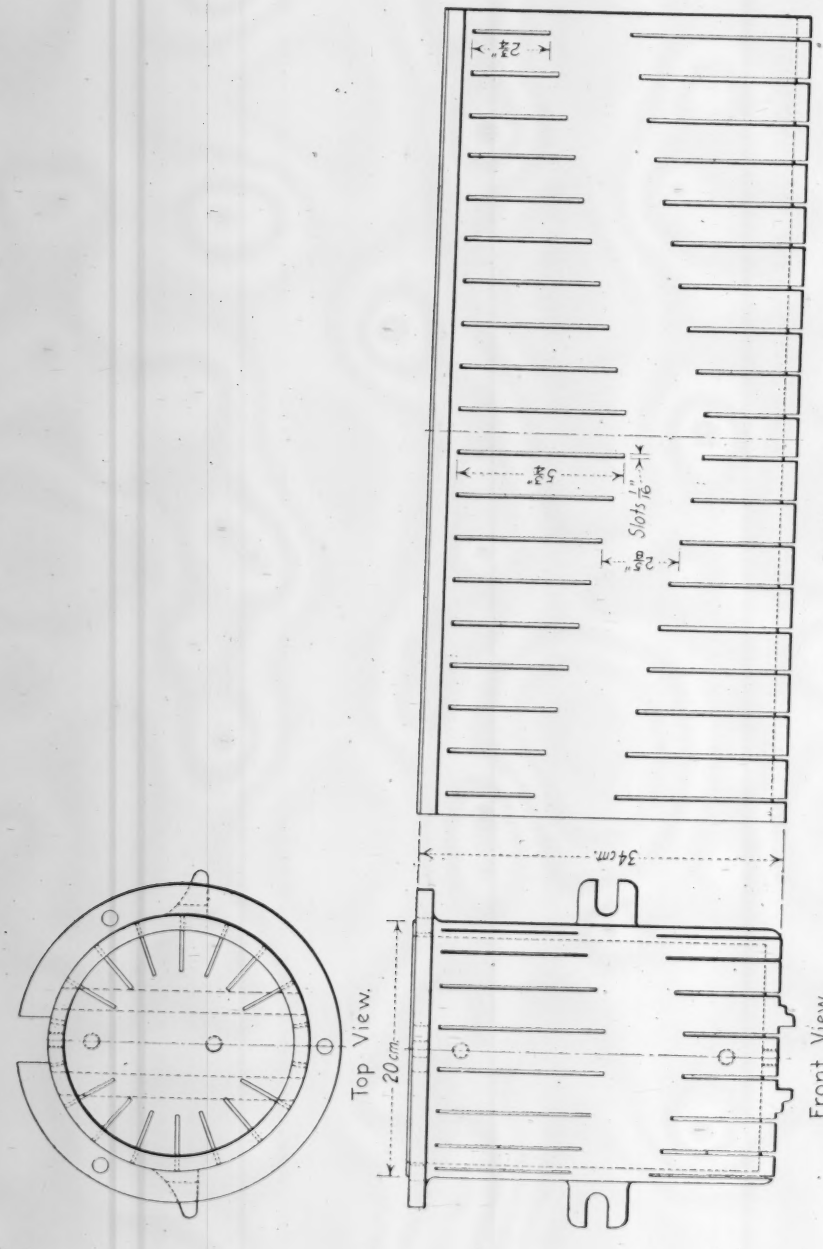


FIG. 3.—Modified De Val Abrasion Cylinder, Showing Arrangement of Slots.

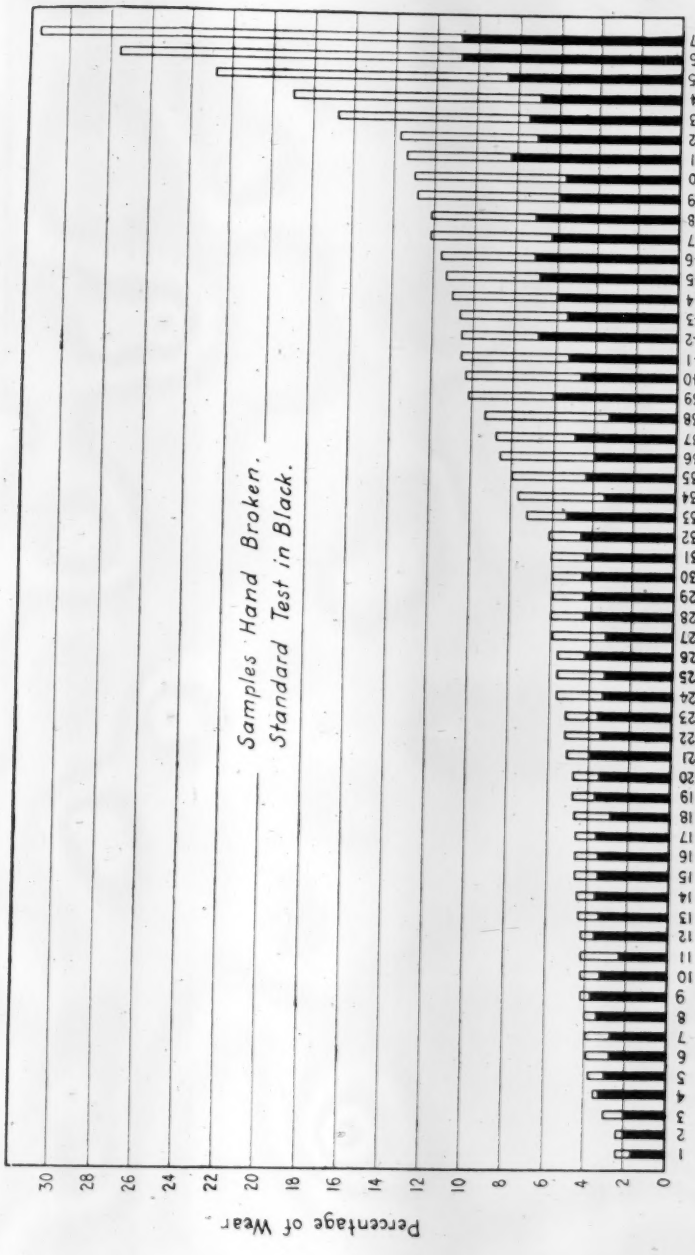


FIG. 4.—Diagram Showing Comparative Range in Percentage of Wear of Rock Tested in the Standard and Slotted Abrasion Cylinders.

TABLE II.—RESULTS OF COMPARATIVE ABRASION TEST FOR ROCK.

No.	Type of Rock.	Hardness.	Toughness.	Percentage of Wear, Standard Test.	Percentage of Wear, Slotted Test.	Difference.
1	Trap	18.7	35	1.6	2.4	0.8
2	"	18.7	..	2.0	2.4	0.4
3	"	18.0	32	2.0	3.0	1.0
4	Granite	19.0	10	3.2	3.5	0.3
5	Trap	18.5	43	3.0	3.8	0.8
6	"	17.3	21	2.7	3.9	1.2
7	"	....	..	2.7	4.0	1.3
8	Granite	18.0	14	3.4	4.0	0.6
9	"	18.7	10	3.7	4.2	0.5
10	"	18.0	14	3.2	4.2	1.0
11	Trap	18.0	26	2.3	4.2	1.9
12	Granite	18.0	9	3.6	4.2	0.6
13	"	18.7	13	3.3	4.3	1.0
14	"	18.7	10	3.5	4.4	0.9
15	Quartzite	18.7	16	3.4	4.5	1.1
16	Granite	18.7	9	3.4	4.5	1.1
17	"	18.7	10	3.5	4.5	1.0
18	Trap	18.0	20	2.8	4.6	1.8
19	Granite	19.3	11	3.6	4.7	1.1
20	"	18.7	10	3.4	4.7	1.3
21	"	18.0	10	3.8	5.0	1.2
22	Quartzite	18.7	17	3.3	5.1	1.8
23	Limestone	17.2	15	3.5	5.1	1.6
24	"	17.3	..	3.3	5.6	2.3
25	Granite	16.7	8	3.2	5.6	2.4
26	"	17.3	7	4.2	5.6	1.4
27	Trap	18.3	18	3.2	5.8	2.6
28	Granite	17.3	7	4.2	5.9	1.7
29	"	16.7	8	4.3	5.9	1.6
30	"	....	7	4.4	5.9	1.5
31	"	18.0	9	4.3	6.0	1.7
32	"	16.7	8	4.5	6.1	1.6
33	"	18.0	8	5.2	7.2	2.0
34	Limestone	15.0	10	3.4	7.7	4.3
35	Sandstone	16.7	8	4.3	8.0	3.7
36	Trap	16.7	9	4.0	8.6	4.6
37	Limestone	17.3	15	4.8	8.8	4.0
38	"	12.3	6	3.3	9.3	6.0
39	"	16.0	8	6.0	10.2	4.2
40	"	12.3	6	4.7	10.4	5.7
41	"	13.9	8	5.3	10.6	5.3
42	Granite	18.5	6	6.8	10.6	3.8
43	Limestone	15.7	5	5.4	10.7	5.3
44	"	15.0	7	5.9	11.1	5.2
45	"	16.0	6	6.8	11.4	4.6
46	"	16.5	6	7.0	11.7	4.7
47	"	12.1	9	6.2	12.2	6.0
48	"	13.3	3	7.0	12.2	5.2
49	"	12.7	4	5.9	12.9	7.0
50	"	13.5	6	5.6	13.0	7.4
51	"	15.9	6	8.3	13.4	5.1
52	"	14.3	7	7.0	13.8	6.8
53	"	12.0	7	7.4	16.8	9.4
54	"	10.2	7	6.9	19.1	12.2
55	"	11.0	5	8.5	22.9	14.4
56	"	8.0	5	10.8	27.6	16.8
57	"	4.0	4	10.8	31.4	20.6

to 0.3 per cent by the use of machine-broken fragments. The individual losses, on the other hand, have been increased in varying amounts due to the elimination of the dust cushion. Tests in the closed cylinder using machine-broken fragments showed slightly lower average results than with the standard method, no doubt due to the absence of wedge-shaped or flat pieces which frequently find their way into a sample prepared in the usual way. The results of a number of tests on a large variety of rock types are given in Table II. These results are plotted

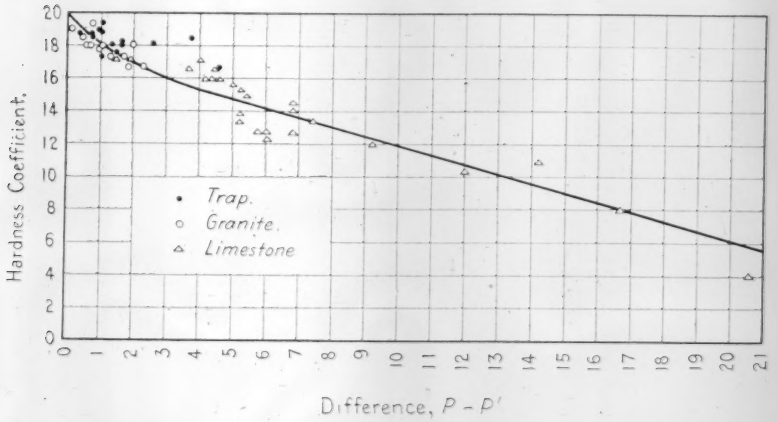


FIG. 5.—Relation Between Coefficient of Hardness and Difference Between the Percentage of Wear as Determined by the Standard Method and with the Slotted Cylinder.

in Fig. 4 in the order of their loss by abrasion in the slotted cylinder. They are of interest in showing the relative effect of the dust cushion as measured by the hardness of the rock. This relationship is plotted in Fig. 5 in which the hardness of the stone determined by the Dorry hardness test[1] is plotted against the difference, P-P', between the abrasion loss in the slotted and in the standard cylinder. Taking into account the fact that all of the test results given in Table II were obtained on samples hand-broken in the usual way and are liable therefore to a possible error of nearly one per cent, the relationship is fairly well defined, and shows clearly the value of using the slotted cylinder in

[1] *Bulletin No. 347*, U. S. Department of Agriculture, p. 6.

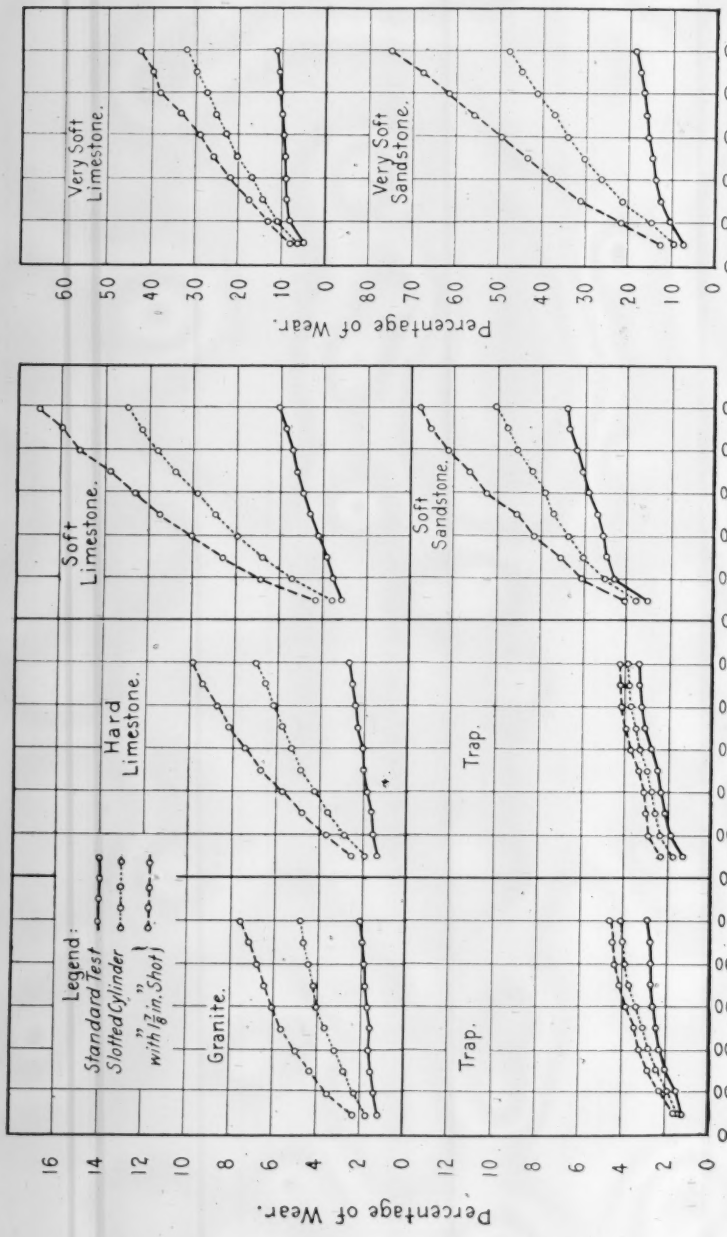


FIG. 6.—Curve Showing the Relation Between Percentage of Wear and Duration of Test.

differentiating between the wearing qualities of the softer types of rock.

In Fig. 6 are plotted the results of a number of tests made in both the standard and slotted abrasion cylinders in which the loss by abrasion was determined at the end of each 1000 revolutions. A comparative run was made also in each case using six $1\frac{7}{8}$-in. cast-iron shot as an abrasive agent. These tests were made in order to determine the practicability of accelerating the wear by means of an abrasive and at the same time speeding up the test by cutting down the total number of revolutions. According to the results shown in the figure it would appear theoretically possible to obtain about the same loss at the end of 2000 revolutions when shot are used as would be obtained at the end of 10,000 revolutions without the abrasive. As a matter of fact, however, experiments have shown that the gain in time thus effected would be more than counterbalanced by the resulting loss in accuracy. It has been found impossible to obtain check tests closer than one per cent when an abrasive is used, due probably to the breaking up of the fragments composing the sample under the action of the shot. This action makes the test a measure of toughness rather than of resistance to wear. Inasmuch as the amount of this action would depend to a large degree on the prevalence of insipient fractures or minute seams in the rock which would not affect the value of the material in road construction, the use of an abrasive is not recommended. The effect of these minute fractures which frequently can not be detected by the eye has been noted in connection with the standard test for toughness of rock.[1]

The following conclusions may be drawn:

1. Results of the standard Deval abrasion test as conducted in the usual way are accurate to within one per cent.

2. The difficulty of properly preparing samples by hand in a reasonable length of time is the principal reason for the discrepancies in results observed.

3. Samples may be prepared conveniently and accurately by means of the machine described in this paper.

4. The range in values of percentage of wear is greatly increased by the use of a slotted cylinder which permits the dust of abrasion to escape as fast as it is formed.

[1] *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part I, p. 414 (1918).

5. In general, the difference between percentage of wear as determined in the standard and in the slotted cylinder increases as the coefficient of hardness of the rock decreases.

In conclusion, the author would strongly recommend that Committee D-4 on Road Materials consider the modifications of the Deval abrasion test outlined above in connection with the proposed revision of the standard method.

NOTE.—Since this paper was written, the laboratory has conducted a cooperative series of tests with other laboratories using the same material. We have, so far, received the results from twelve state testing laboratories and one commercial laboratory. The deviation is almost exactly one per cent, which is about the same as we obtained in our laboratory with different tests of the same material.

DISCUSSION

Mr. H. H. Schofield. **Mr. Schofield.**

Mr. H. H. Schofield (*by letter*).—The general use in specifications for ballast and road material of the percentage of wear as given by the standard abrasion test, makes the subject matter of this paper of considerable importance.

The standard test should be revised in at least two particulars mentioned, that is, the method of preparing the charge to gain uniformity and the removal of the dust cushion in order to give a true test on the softer materials. The writer would suggest that in the revision there be considered the design of a new machine to take the place of the cumbersome and unmachine-like cylinder apparatus now in use. The writer has used a horizontal octagonal abrasion chamber with staves not unlike the rattler for paving brick. In this type the time of test can be greatly shortened by the use of an abrasive charge.

If the abrasive spheres are not large in proportion to the rock particles, the element of toughness will not be over emphasized. It would seem entirely proper that the test should develop resistance to mild impact as well as resistance to abrasion as was originally intended, and that therefore the abrasive agent is of double use.

Mr. Floyd H. Rood (*by letter*).—Mr. Jackson has pointed out the main reason for variations in the results obtained by the Deval abrasion test; namely, the method of preparing the sample for test. Realizing that the shape and size of the pieces made considerable difference in the value of this test, the New York State Commission of Highways has always used a machine for breaking up samples of stone. Such a machine was first used by Mr. Clarke, the State Geologist, for breaking up small samples of rock. It was an old letter press fitted with knife edges similar to those on Mr. Jackson's machine. When the road material testing laboratory was installed in the State Engineer's office about 1905, Mr. R. S. Greenman had one made like it for his use. The small cast-iron frame of the letter press was too light to stand the work required of it and he built another

Mr. Rood. **Mr. Rood.**

Mr. Rood. with a heavier cast-iron frame. This frame finally broke and in 1908 Mr. H. S. Mattimore re-designed it with a heavy steel frame and a larger hand wheel. This is the machine now in use by the Highway Commission and I believe it is the one from which Mr. Jackson got his idea.

Two men, one to operate the wheel and the other to place the stone in the machine, can break up a sample ready for the abrasion test in about ten minutes. One man alone can do it in about twenty minutes.

Wear on the pieces of stone in the Deval machine is largely on the edges. A cube has a shorter length of edge than any other angular specimen of the same volume. Most samples of stone are easily broken by the machine into cubical pieces of uniform size, while it is almost impossible to secure such pieces by hand breaking. Consequently when the sample is broken by machine the wear will be slightly less than when broken by hand. Also the percentage of loss on different tests of the same stone will show less variation when the pieces are of uniform shape and size.

Mattimore began using a slotted standard cylinder for the Deval test in 1915.[1] Several comparative tests were made with this cylinder and the standard cylinder in which the charge of stone was removed every 500 revolutions from the standard cylinder and both the cylinder and stone thoroughly brushed clean of dust. In practically every case the loss in the standard cylinder checked that in the slotted cylinder at the end of the 10,000 revolutions.

These tests, together with those of Schofield and Jackson, show that the way to obtain the best results from the abrasion test is to remove the dust as fast as it forms in order to get away from its cushioning effect. This is particularly true with the softer stones.

In conclusion I would emphasize Mr. Jackson's recommendation that Committee D-4 on Road Materials consider the use of a machine for preparing samples of stone for the Deval abrasion test, and a slotted cylinder to remove the dust as fast as it forms.

[1] A photograph of his cylinder and some of the results of his tests are given in *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Part II, pp. 426–428 (1918).

MR. K. A. CLARK (*by letter*).—The abrasion test has been a subject to which I have given considerable thought and work during the past few years. I wish to record some of my observations and conclusions as a contribution to the discussion of Mr. Jackson's paper. **Mr. Clark.**

Tests such as the abrasion test for rock are devised for the practical purpose of measuring the value of some property of a supply of material whose use in constructional work is being considered. The result of a test depends on factors involved in the taking of the sample of the material about which information is sought, in the nature and design of the test itself and in the care with which the test is carried out. Since it is the maximum source of error that will determine the value of the test results, there is no real advantage gained in adding refinement to either sampling, test design or manipulation unless at the same time all three processes are brought to the same degree of perfection. A manipulation that enables one to duplicate results closely is of no value if along with such refinement there is no corresponding refinement in sampling so that the sample upon which work is done represents as closely the material about which information is wanted or in the principle of the test so that as accurate a measure is made of the property in question.

Mr. Jackson describes an improved manipulation for preparing the test pieces for the abrasion test which enables him to get much better check results. His manipulation, however, involves a laxity in sampling that to my mind makes most improbable a representative sample. Rock deposits, with the exception of some very uniform ones used for the manufacture of paving block and building stone, contain material varying through a considerable range of texture and composition. Sedimentary deposits vary from bed to bed while deposits of igneous origin are liable to variation in all directions of quite pronounced character. Crushed stone is produced by crushing rock blown down from a face on which may be exposed material varying over quite a range. The fifty pieces specified for the abrasion test provides a splendid opportunity for making the sample representative. If the sampling is done by a competent person and the fifty pieces collected across the face so as to include variations in the proper proportion, a good sample is bound to be secured on which care

Mr. Clark. in testing is warranted. But if the sample consists of two or three fair-size blocks which are to be broken up in the laboratory to make the fifty pieces, I fail to see where there is any guarantee, or even probability, of a representative sample. Splitting the blocks into nice cubes with a machine to get samples that check closely can never correct bad sampling and the results, no matter how concordant, will be probably an untrue return on the property of the rock being evaluated.

TABLE I.—LOSS IN WEIGHT FOR EACH SUCCESSIVE 1000 REVOLUTIONS IN THE DEVAL ABRASION MACHINE (STANDARD AND SLOTTED CYLINDERS) OF 5000-GRAM CHARGES OF A DURABLE, INTERMEDIATE AND SOFT TYPE OF ROCK.

Number of Revolutions.	Loss of Weight, grams.					
	Diabase.		Limestone.		Marble.	
	Standard.	Slotted.	Standard.	Slotted.	Standard.	Slotted.
1 000	59	63	89	105	143	189
2 000	13	17	19	68	33	103
3 000	18	23	11	45	18	93
4 000	5	33	11	47	6	78
5 000	5	20	9	38	22	65
6 000	7	23	9	48	10	67
7 000	13	15	17	29	6	63
8 000	10	13	2	28	11	50
9 000	2	25	11	35	0	60
10 000	13	8	12	30	11	40
Washed[1]	15	2	28	3	55	6

[1] At end of run, samples were washed, dried and weighed to determined weight of dust that was caked onto surfaces of pieces.

I will show later on that the practice of preparing the abrasion sample in the uniform cubes exaggerates a disturbing factor in the nature and design of the test itself.

A durable type of rock represented by a diabase, an intermediate type represented by a limestone and a soft type represented by a metamorphosed limestone or marble were recently subjected to an experimental run in the abrasion machine of the Mines Branch, Department of Mines, Ottawa. Duplicate samples, as nearly identical as possible, were secured of each type. These duplicate pairs were then put through a run of 10,000 revolutions in the Deval abrasion machine, one in a standard type of cylinder and the other in a cylinder modified

by being slotted as described by Mr. Jackson. The run was interrupted at the end of each 1000 revolutions and the loss in weight suffered by the charge determined. Loose dust adhering to the pieces was removed by striking them together as they were being taken from the cylinder. The results of the experiment are given in Table I. Some deductions from these figures are presented in Table II. Mr. Clark.

TABLE II.—LOSS IN WEIGHT DURING FIRST 2000 REVOLUTIONS, LAST 8000 REVOLUTIONS AND DURING WHOLE RUN FOR SAMPLES OF DIABASE, LIMESTONE AND MARBLE REFERRED TO IN TABLE I, IN THE STANDARD AND THE SLOTTED CYLINDERS OF THE ABRASION MACHINE. ALSO RELATIVE TENDENCIES TO WEAR OF THE THREE TYPES OF ROCK AS DETERMINED BY EACH PART OF THE RUN AND BY THE WHOLE RUN, IN BOTH TYPES OF CYLINDERS.

	Diabase.	Limestone.	Marble.
Loss in grams during first 2000 revolutions, standard cylinder	75	114	187
Relative tendency to wear	1	1.5	2.5
Loss in grams during last 8000 revolutions, standard cylinder	85	104	128
Relative tendency to wear	1	1.2	1.5
Loss in grams during whole 10,000 revolutions, standard cylinder	160	218	315
Relative tendency to wear	1	1.4	2.0
Loss in grams during first 2000 revolutions, slotted cylinder	80	174	293
Relative tendency to wear	1	2.2	3.7
Loss in grams during last 8000 revolutions, slotted cylinder	162	302	521
Relative tendency to wear	1	1.9	3.2
Loss in grams during whole 10,000 revolutions, slotted cylinder	242	476	814
Relative tendency to wear	1	2.0	3.4

(The weight of dust caked on the pieces at end of run is evenly distributed over whole run in calculating figures in Table II.)

The diabase rock chosen was what common sense would determine as a very durable type, while the marble would be classed as a rock decidedly soft to be of much value as a road material. The limestone held an intermediate position in respect to durability. The abrasion test, stopped at the end of the first 2000 revolutions, values the tendency of the three types to wear in the ratio of 1:1.5:2.5. The last 8000 revolutions, however, value this property in the ratio of 1:1.2:1.5; while the

Mr. Clark. complete standard abrasion test gives the ratio as 1:1.4:2.0. These figures show up very forcibly the effect of the cushioning action of the dust in the standard cylinder. It coats not only the cylinder but also the surfaces of the pieces and after the first 2000 revolutions little wear takes place. But what is worse is that all types of rocks wear at about the same rate without much relation to their actual durability. To say the least, the results of the standard abrasion test bear a very obscure and complicated relation to the actual wearing quality that is being tested.

There is still another disturbing factor beside the cushioning action, affecting the validity of the abrasion test. This factor is shown up by the part of Table II referring to the slotted cylinder. The different periods of the test still do not tell the same story about the relative wearing quality of the three types of rock although the results are much more concordant than in the case of the standard cylinder. The reason for this is that wear first takes place rapidly while corners and edges are sharp, the rate of wear decreasing as a uniformly rounded surface is developed on the pieces. The result of an abrasion test can be considered as the summation of the results of ten 1000-revolution tests, each test being expressed in successlvely smaller units of wear. It is like adding fractions without first bringing them to a common denominator. As a consequence even the results of the modified abrasion test with the cushioning action eliminated are not a true measure of the wearing quality and do not stand in the same relation, one to another, as the actual wearing qualities of the materials that have been tested. The rate of change is not great, however, after the first 2000 revolutions. Comparison of the wear produced during the last 8000 revolutions of the test will give a far better relation of the true wearing quality of rocks than the first 2000 or the whole 10,000 revolutions.

This consideration constitutes another viewpoint for judging of the merit of the modification proposed by Mr. Jackson for preparing abrasion samples. A glance at his Table I shows that much higher results are obtained by preparing the samples as he suggests. This is to be expected, since angularity is developed to the limit and consequently the test is started off at the highest possible rate of wear and with a high rate con-

Mr. Clark.

tinuing for a longer period of the test before the corners are worn down and rounded surfaces developed. It seems to me that the aim should be to prepare the sample so as to reduce to a minimum the angularity of the pieces so that the wear produced during the whole period of the test may be at the same rate, or with as little change as possible.

I should like to suggest as a line of investigation, experiments with abrasion test charges consisting of pieces which have been rounded instead of made as square as possible. The rounding could be done by a preliminary 2000 revolutions run in the slotted cylinder. Preparation of a rounded set of pieces could be made perfectly consistent with good sampling when the fifty pieces are produced at the deposit and in such a way as to properly represent variation in the material supply. The test would be better in principle with the rounded pieces, since the wear would be done at a fairly constant rate throughout the whole period of the operation. Finally, with such a type of charge, it seems to me it would be possible to test directly a crushed stone product, the material which is actually to be used.

SOME RELATIONS BETWEEN THE CHARACTERISTICS OF STEAM-DISTILLED PETROLEUM RESIDUALS.

By B. A. Anderton.

In the interpretation of the results of tests on bituminous road materials, it is well understood that a given set of values must be considered as a whole; in other words, the significance of almost any result is dependent upon other results or combinations of them. So in the preparation of specifications, the selection of suitable requirements to secure the desired materials must therefore be done with the influence of other requirements always in mind. We have all seen specifications for asphalts and road oils with which no commercial product could possibly comply on account of some unattainable requirement.

TABLE I.—CHARACTERISTICS OF CRUDE PETROLEUM AS SHOWN BY TESTS ON THREE TYPICAL PETROLEUMS.

	Petroleum, Source.		
	California, Kern River.	Texas, Sour Lake.	Mexico, Panuco.
Water, per cent by volume	6.0	0.0	2.9
Specific gravity 25°/25° C.	0.965	0.935	0.985
Flash point, deg. Cent.	115.	54.	52.
Burning point, deg. Cent.	....	122.	110.
Specific viscosity, Engler, 25° C.	....	22.8	....
" " " 50° C.	....	5.25	....
" " " 100° C.	2.82	1.60	....
Float test, 32° C., seconds	....	....	40.6
" " 50° C., "	8.6	....	26.5
" " 70° C., "	6.6	....	16.5
Loss at 163° C., 5 hours, 50 g., per cent	8.76	15.70	11.77
Float test residue, 50° C., seconds	20.8	4.9	78.3
" " " 70° C., "	....	....	38.3
Bitumen insoluble in 86° B. naphtha, per cent	3.40	0.31	20.09
Fixed carbon, per cent	3.58	1.38	10.77
Organic matter insoluble, per cent	0.01	0.07	0.09
Inorganic matter insoluble, per cent	0.00	0.06	0.00
Total Bitumen (Soluble in CS_2), per cent	99.99	99.87	99.91

The writer is not aware that there is in the literature on bituminous materials any great amount of data on the relationships between the various tests with regard to the types of crude petroleum involved, and particularly as affected by the variations

in process of manufacture. With the experience of many years' testing of bituminous materials, some general conclusions have been well brought out; as, for example, the relatively high specific gravity, insolubility in petroleum naphtha, and percentage of fixed carbon of products from Mexican petroleum;

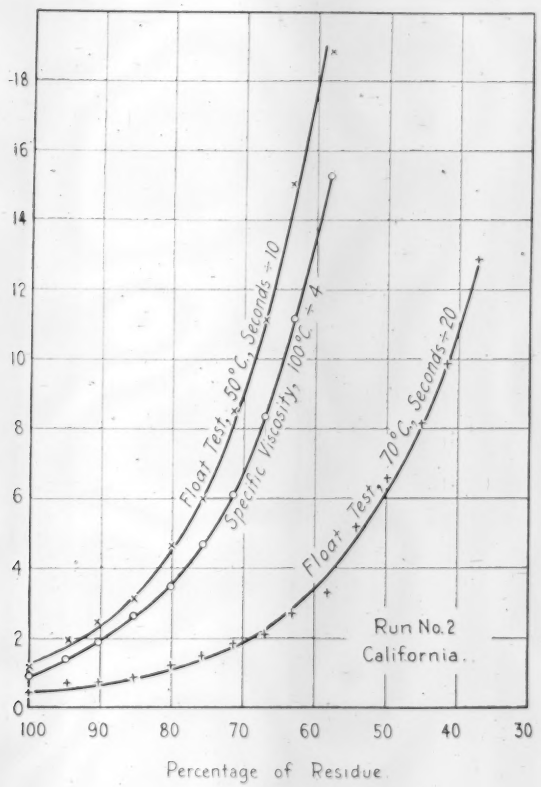


FIG. 1.—Typical Tests of Consistency with Progress of Distillation.

also, the relatively low ductility, high melting point, and high insolubility in naphtha of blown oils. But, in general, it is quite difficult to correlate available data in order to demonstrate specific relations along these lines, and in this communication the writer will endeavor to make some contribution to the subject

which, while not entirely new material, may be of interest as setting forth in a definite manner the significance of some of our present tests.

The opportunity to study the characteristics of petroleum residuals in this manner comes as a result of the operation of a

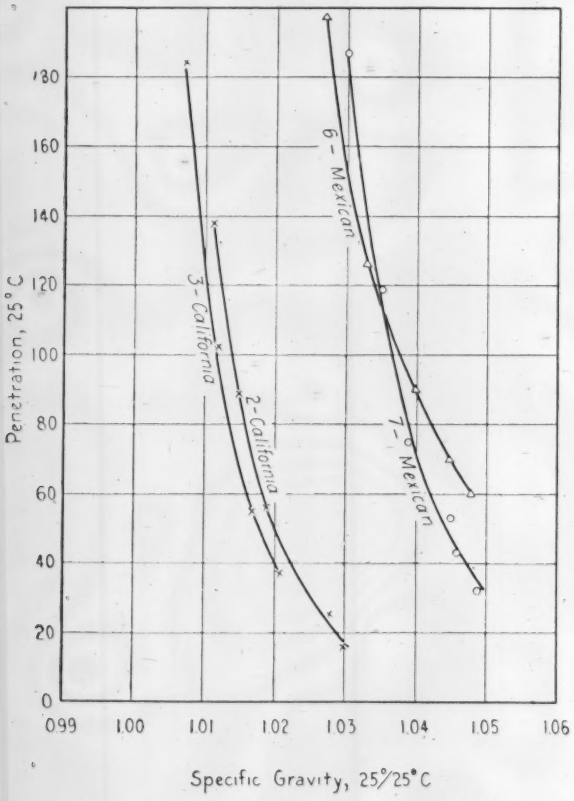


FIG. 2.—Penetration of California and Mexican Asphalts Showing Greater Specific Gravity of Mexican Products.

small experimental refinery by the U. S. Bureau of Public Roads. A number of runs have been made, all of which up to the present time have involved steam distillation. Three typical crude petroleums have been used from California, Southern Texas, and Mexican fields, respectively, whose important characteristics are shown in Table I. During each distillation steam was passed

through the still at such a rate as to maintain a fairly constant ratio of water to oil distillate in the flow from the condenser. These ratios were as follows:

PETROLEUM.	RUN NO.	AVERAGE STEAM RATIO.
California	1	0.69
"	2	1.21
"	3	0.92
Texas	4	0.75
"	5	0.55
Mexican	6	0.65
"	7	0.83

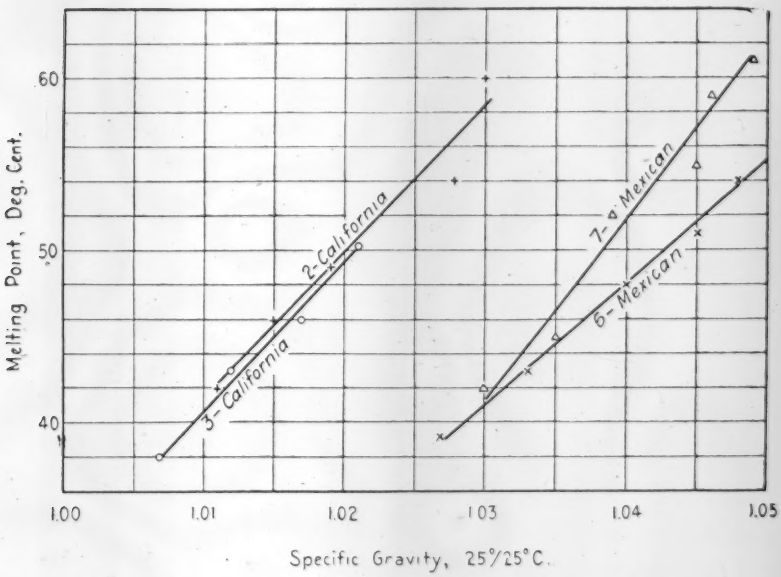


FIG. 3.—Melting Points of California and Mexican Asphalts Showing Greater Specific Gravity of Mexican Products.

As distillation proceeded, samples were taken systematically from the experimental still and tested, following the standard methods of the Society whenever they were applicable. Otherwise, tests were carried out according to the methods in use by the Bureau of Public Roads.[1] It can readily be seen

[1] "Methods for the Examination of Bituminous Road Materials," *Bulletin No. 314*, U. S. Department of Agriculture.

that these series of samples, all produced from the same still-charge of petroleum, and representing the changes in characteristics of the residuals taking place as the distillation continued, permit a study of interrelations between tests which could not ordinarily be accomplished with a collection of miscellaneous samples, affected possibly in different degree by variations in the original crude and in method of treatment. As an example of the development in consistency as the distillation progressed,

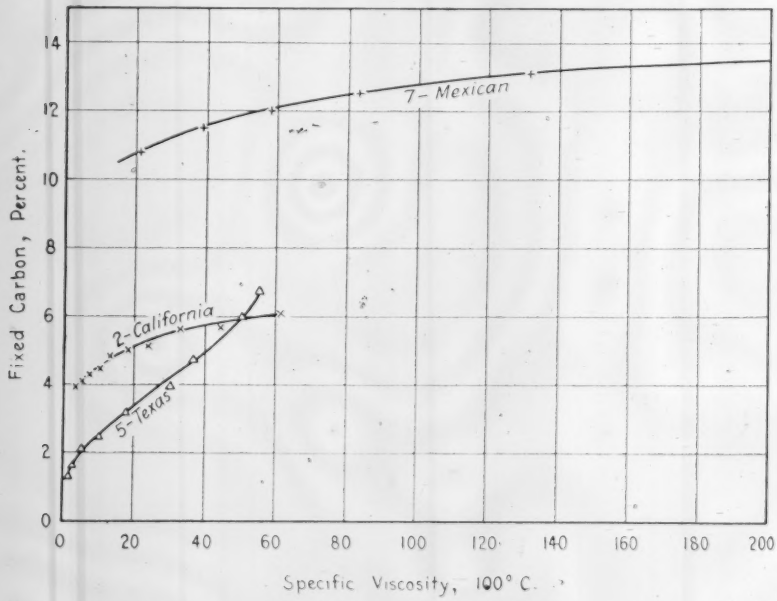


FIG. 4.—The Fixed Carbon of Typical Fluid Residuals.

Fig. 1, representing the specific viscosity and float tests of residues secured in one distillation of California petroleum, may be shown. Abscissæ indicate the percentage of the crude removed as distillate or, on the scale given, the percentage of residue in the still. These curves are typical, not only of the graphical representation of other test results, but of other crudes. With very few exceptions, a smooth curve can be drawn with such plotted points, representing the actual relation of the two variables fairly well.

Within the space of the present paper it will be possible to discuss only the most prominent relations which have presented themselves as a result of the work so far, which, as may be mentioned again, has all dealt with steam distillation. The samples examined should be considered as typical of their type; and little attempt will be made to discuss the test results theoretically, or to derive mathematical relationships, as it is felt that the scope of the available data is at present too limited for

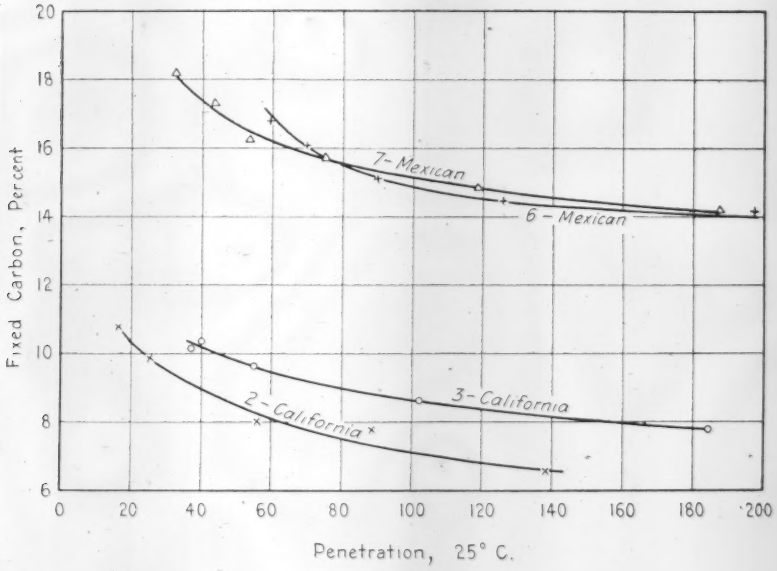


FIG. 5.—The Fixed Carbon of Typical California and Mexican Asphalts.

discussion of that nature. The data are presented graphically, requiring in most cases little explanation or comment.

Tests have shown clearly the greater density of Mexican asphalts. In Fig. 2, asphalts up to 200 penetration produced from the Mexican petroleum have a specific gravity of about 0.02 to 0.03 higher than for corresponding California products. It will be noted that there is a distinct difference in the two curves 6 and 7, although in both runs the crude was the same Mexican petroleum. This may be explained by the use of a greater volume of steam during distillation 7.

In Fig. 3 the greater specific gravity of Mexican asphalts than of California asphalts for a given melting point is shown. The difference is more significant when it is borne in mind that a California asphalt of the same melting point is considerably harder at normal temperature, as will be shown later. In Fig. 3

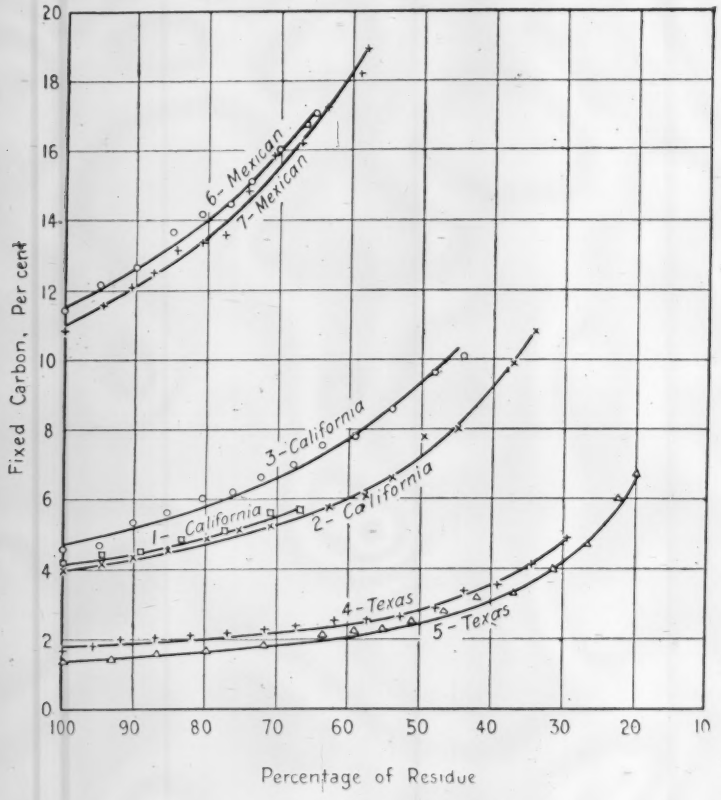


FIG. 6.—The Development of Fixed Carbon in Steam Distillation.

it has seemed best to represent the relations as straight lines, owing to the small number of points and having in mind the accuracy of the tests. The divergence between the two Mexican series is again noted.

Considering the percentage of fixed carbon in Mexican, California, and Texas residuals, Fig. 4 will show the high per-

centage for Mexican products, increasing slowly with specific viscosity at 100° C. The Texas residuals increase rapidly in fixed carbon, but it is of interest to note that the final point on this curve represents a residue of only 20 per cent of the crude oil, attained at a high still temperature. The Texas petroleum would produce by steam distillation alone only a small quantity of residuals suitable for road work, and most likely of an inferior quality.

The higher fixed carbon for Mexican asphalts of less than 200 penetration is demonstrated in Fig. 5. Comparison with

TABLE II.—PRODUCT OF FIXED CARBON BY PERCENTAGE RESIDUE OF STILL CHARGE.

Designation of Residue.	California			Texas		Mexican	
	1	2	3	4	5	6	7
R0	4.15	3.95	4.52	1.68	1.38	11.48	10.80
R1	4.17	3.87	4.40	1.72	1.34	11.58	10.95
R2	3.99	3.87	4.81	1.74	1.39	11.42	10.95
R3	3.99	3.83	4.79	1.71	1.32	11.66	10.93
R4	3.89	3.88	4.48	1.64	1.32	11.46	11.08
R5	3.75	3.80	4.70	1.54	1.36	11.17	10.79
R6	3.79	3.64	4.75	1.56	1.31	11.18	10.55
R7	....	3.76	4.74	1.57	1.25	11.27	11.06
R8	....	3.59	4.82	1.52	1.28	11.11	11.26
R9	....	3.52	4.64	1.45	1.31	11.08	10.86
R10	....	3.58	4.67	1.38	1.35	.....	10.91
R11	....	3.89	4.68	1.39	1.24	.....	10.71
R12	....	3.60	4.49	1.45	1.26	.....	10.92
R13	....	3.70	....	1.41	1.27	.....	.....
R14	....	3.71	....	1.41	1.35	.....	.....
R15	....	3.44	....	1.46	1.35	.....	.....
R15A	....	....	....	1.32	1.29	.....	.....
Average	3.96	3.66	4.65	1.53	1.32	11.34	10.91
Mean deviation	0.13	0.14	0.12	0.11	0.04	0.18	0.12
Maximum deviation	0.21	0.29	0.25	0.21	0.08	0.32	0.36

Fig. 2 will show that the form and relation of the two Mexican curves is similar, indicating a closer relation between specific gravity and fixed carbon.

An interesting relation which apparently is independent of the type of oil used, and which may point out the specific value of the fixed carbon test, should be discussed at this point. If the percentage of fixed carbon for successive residues is plotted against the percentage of residue, as in Fig. 6, it is noticed that in general the plotted points show a tendency to lie along the curve of a hyperbola. Also, by multiplying the percentage of

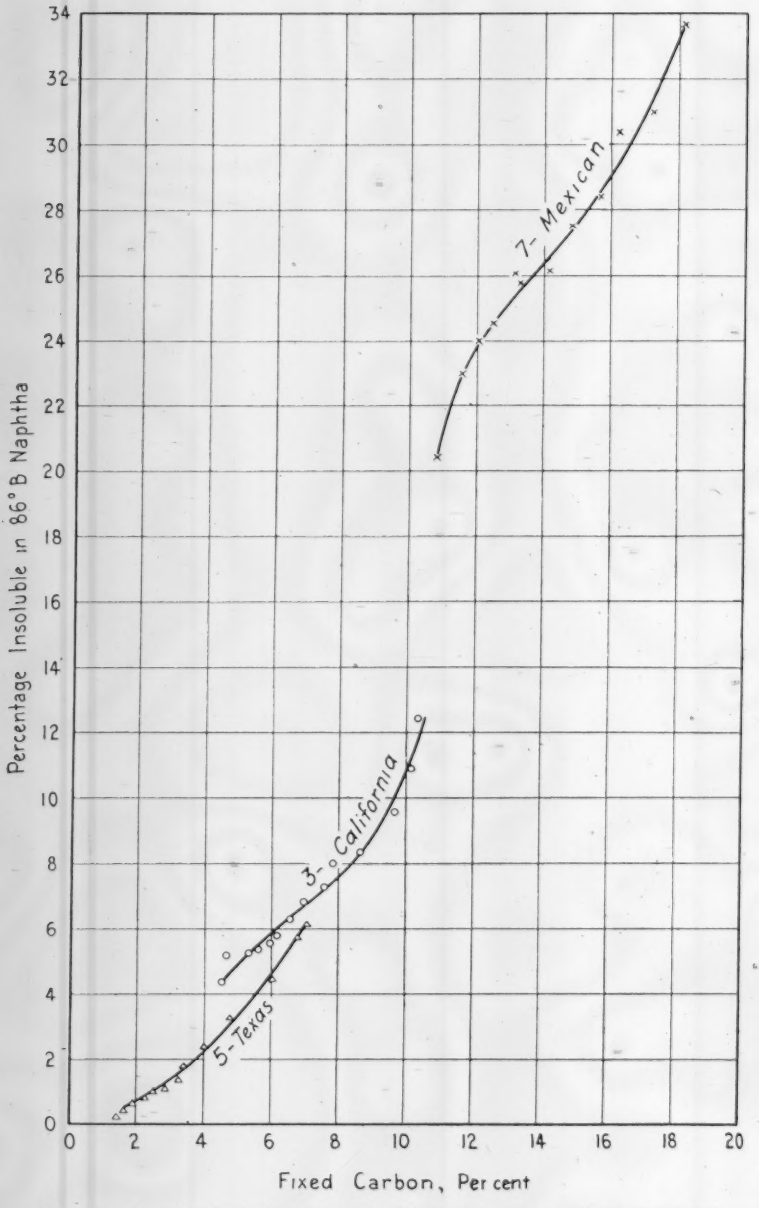


FIG. 7.—General Relation Between Fixed Carbon and Percentage of Bitumen Insoluble in 86° B Naphtha.

fixed carbon by the percentage of the still charge represented by the corresponding residue, the series of values shown in Table II is obtained.

It will be seen that for all distillations the values for a given run are practically constant. Judging from the deviations

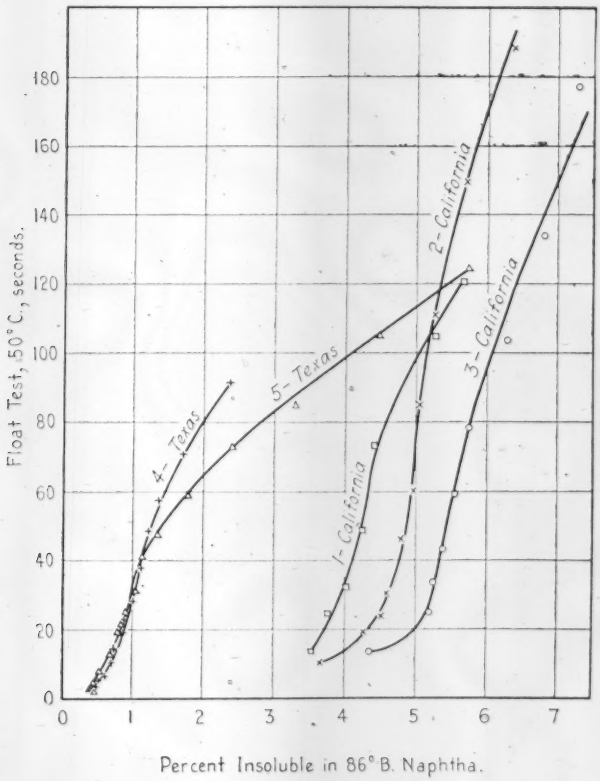


FIG. 8.—The Naphtha Insoluble of Fluid Texas and California Residuals.

from an average value, they are as constant as should be expected with the fixed carbon test. Accepting the constancy of the product, the relation may then be expressed by the equation

$$RC_R = 100\ C_{100}$$

where C_R is the percentage of fixed carbon of a steam distilled

petroleum residual, which is R per cent of the original having a fixed carbon of C_{100} per cent. In this connection it may be noted that subsequent work in which residuals have been air-blown has shown that blowing materially increases the percentage of fixed carbon.

In Fig. 7 the general tendency of the fixed carbon and percentage of bitumen insoluble in 86° Baume naphtha to increase together is shown.

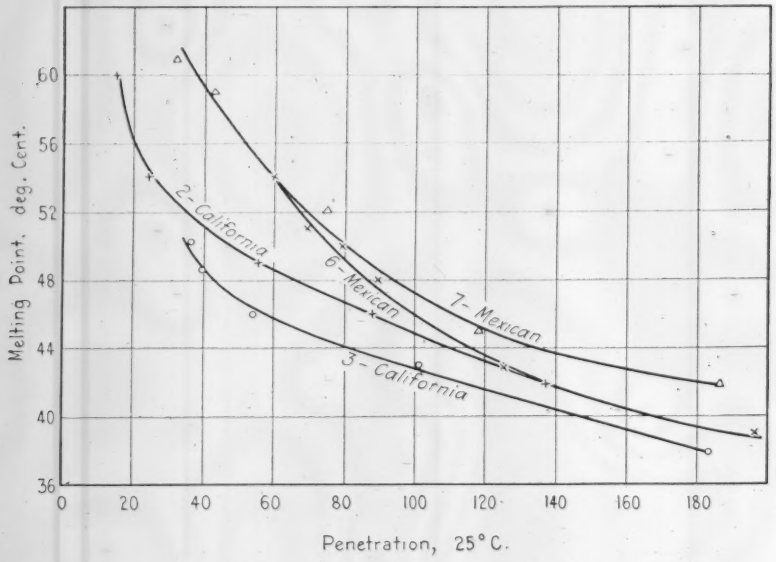


FIG. 9.—The Melting Point of Mexican and California Asphalts.

The proportional rate of increase for a given material, however, evidently varies quite widely, and in this curve, as in some others involving naphtha insoluble, it is indicated that at some point in the distillation, reactions begin within the petroleum, gradually increasing in importance as the temperature rises, which result in the actual formation of bodies of an asphaltic character. Particularly is this evidenced in Fig. 8, when the naphtha insoluble is plotted against consistency by the float test at 50° C.

The reversal of curvature is quite striking in this diagram. If the point at which the curvature reverses is estimated from the

graphs, and taken at a float test of 30 seconds for the Texas, and 60 seconds in the case of the California, it may be of interest to add that the temperature of the Texas oil at this point in the distillation was 295–300° C., while the California oil had a temperature of 250–260° C.

That some asphaltic products soften more readily upon heating than others and that this susceptibility to heat may be greatly modified by variation in the process of manufacture, are well understood facts. In specifications for paving asphalts,

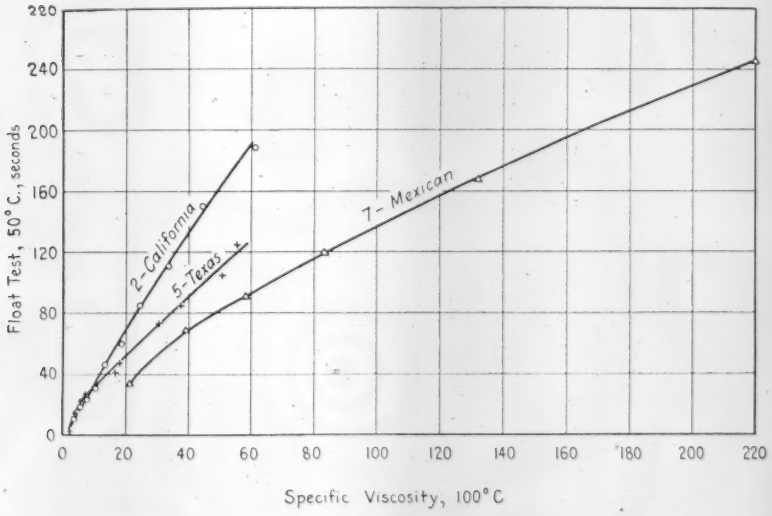


FIG. 10.—The Float Test of Typical Fluid Residuals.

therefore, various combinations of requirements for melting point, ductility, penetration at 0° or 46° C., etc., together with the consistency at normal temperature, are utilized to secure a material having suitable qualities for the particular work in hand. The variation in ball and ring softening point for typical Mexican and California asphalts is shown in Fig. 9.

Another test which, though looked upon usually as a consistency test, is not often utilized to investigate susceptibility to temperature may be used to advantage on a wide range of products. This is the float test. That this test is essentially a test of

viscosity is made apparent by the great similarity of the curves shown in Fig. 1. The results of the float test are, however, greatly influenced by the way in which the material tested softens on heating, and consequently, as the bath temperature is set at a higher point, the test becomes more and more a measure

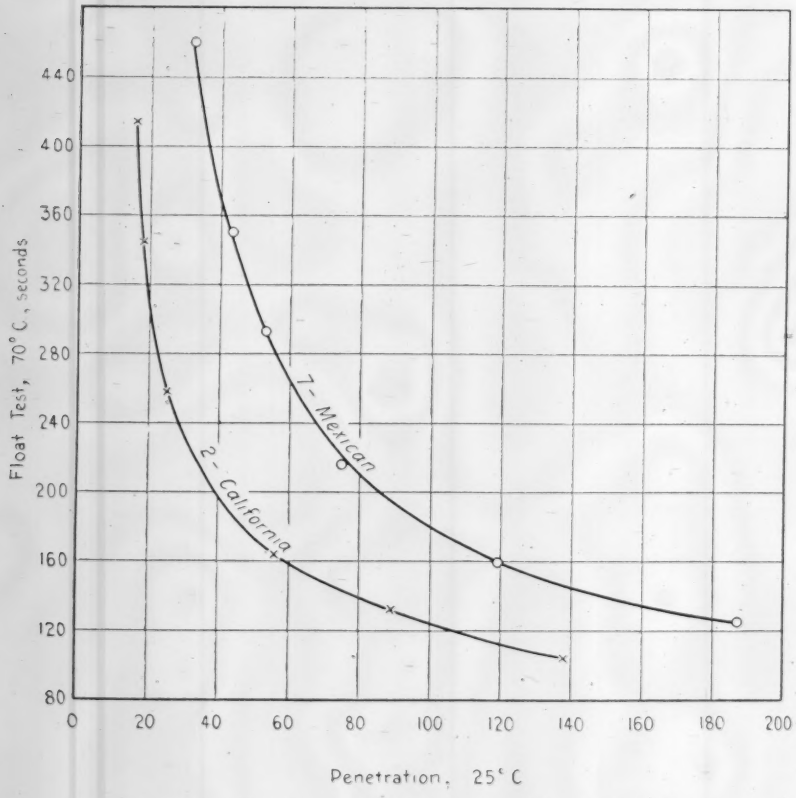


FIG. 11.—The Float Test of Mexican and California Asphalts.

of the susceptibility of the material. It may be considered as giving a measure of viscosity combined with susceptibility. Figs. 10 and 11 will illustrate this. In Figure 10, the California, Texas, and Mexican products show a decreasing susceptibility, in this order, by having a lower float test at a lower temperature, for the same specific viscosity at 100° C.

A large number of float tests have been made at 70° C., in order to secure data on the change in consistency over a wide range of products, especially to cover the range of consistency where the viscosity test at 100° C. or the penetration at 25° C. is not readily applicable. The results of these tests on the harder asphalts also indicate the greater susceptibility of the California products, as may be seen in Fig. 11.

As the penetration increases, the difference in float test becomes more marked; at 35 penetration the Mexican asphalt gives a float test twice that of the California asphalt.

It will be realized that the relations which the writer has tried to bring out graphically represent data compiled from typical petroleums only, and that the characteristics of residual oils and asphalts may be greatly modified by changes in method of refining. In the writer's judgment, two features—the significance of the fixed carbon test in relation to the progress of steam distillation and the development of the float test as a measure of viscosity and susceptibility to temperature changes—should prove the two points of greatest interest and value in this communication.

DISCUSSION.

Mr. Smith. MR. F. P. SMITH.—I should like to ask Mr. Anderton if the equation he gives should not also take into account the amount of steam used. If in a particular run you start with ample steam, and toward the end of the run cut down the steam, you would not maintain the relation between the fixed carbon and the constants. Take any one of the runs that are described in the paper: if ample steam has been used for the first 50 per cent of the distillation, and then the steam is cut down, an end product will be obtained which has a much higher percentage of fixed carbon, and the reduction of the unit percentage of that residue will not keep pace with the increase in fixed carbon in the material. Will not that change the relations expressed by the formula?

Mr. Anderton. MR. B. A. ANDERTON.—I do not believe so, where ample steam is used, as in these experimental distillations. In each case the product remains constant and yet as between different runs there is considerable variations in the quantity of steam used. Since we may assume in the equation

$$RC_R = 100C_{100}$$

the amount of residue left at any point as the initial charge, irrespective of the amount of steam

$$R_1C_{R_1} = R_2C_{R_2}$$

then I should not suppose that the variation in the amount of steam itself used in the distillation would affect the percentage of fixed carbon.

Mr. Smith. MR. SMITH.—Let us take the end point of a Mexican crude, for example, to be a residue of 50 penetration. It is possible to run that distillation with an amount of steam which will give an end product having 14.5 to 15.5 per cent of fixed carbon. That distillation, with exactly the same crude, can be run with less steam and in a different manner so as to give a fixed carbon content of 18 to 19 per cent; and yet there will be very little

difference in the percentage of residue obtained as compared with the original still charge. Such being the case, it would seem to me that that formula would have to take into consideration the amount of steam used, in order to be generally applicable. Mr. Smith.

MR. ANDERTON.—If I understand your statement correctly, it would seem that under such conditions, that quantity would necessarily have to be included in any equation for general application. Mr. Anderton.

I would say that so far, we have intentionally not changed the amount of steam used to any great extent during the distillation. Of course we have had unavoidable slight changes. The results of these runs are presented at this time with only such conclusions as can be based on the selected conditions under which they were made, and as limited by those conditions.

MR. PRÉVOST HUBBARD.—I should like to ask Mr. Anderton if he included Mexican in the series of comparisons? If so, did the Mexican develop the same general relations that are shown by the other two types? Mr. Hubbard.

MR. ANDERTON.—The Mexican runs were not carried so far, of course; and although there was a slight indication of a curvature of the same nature in the naphtha insoluble relation for the Mexican, it was not so noticeable as in the case of the Texas and California oils. Mr. Anderton.

THE SO-CALLED ASPHALT CONTENT OF ROAD OILS.

By B. A. Anderton and D. G. Taylor.

The grading of asphaltic road oils on the basis of the percentage of asphalt contained in them is still in extensive use as a means of differentiating between various types of oils—that is, as between their inherent nature and consistency. Notwithstanding that there are obvious difficulties in making the test, and that its value has been for some time severely criticized, a conference of state highway testing engineers and chemists, held in Washington in 1917, deemed the test of such extensive use as to warrant including it as an alternate requirement in forms of specifications drawn up for road oils. The method of making the test was also considered, and in the report[1] of the conference the recommended procedure to be followed is given, as follows:

PERCENTAGE OF RESIDUE OF ..... PENETRATION.

Fifty grams of oil are placed in a 3-oz., deep, seamless tin box; the box is placed in a sand bath and heated over a Bunsen burner. A thermometer is suspended in the oil, the bulb not touching the bottom of the box. The temperature of the oil is kept at from 249 to 260° C. (480 to 500° F.), and the oil is stirred from time to time with the thermometer to prevent overheating in any part. Depending upon the nature of the oil, as usually indicated by its flash, consistency at 25° C. (77° F.), and the specific gravity, the operator can with experience tell about what percentage it will be necessary to evaporate before cooling and taking a penetration of the residue. It is sometimes necessary to make several trials before the desired result is obtained. When the required penetration is reached, the residue left from evaporation is weighed and its percentage of the original sample taken is computed.

The Bureau of Public Roads, with a desire to investigate how closely the various characteristics of a sample would indicate the percentage of residue of 100 penetration, as suggested in this description of the test, has made a large number of determinations following the procedure given as closely as possible. From

[1] "Standard Forms for Specifications, Tests, Reports, and Methods of Sampling for Road Materials," *Bulletin No. 555*, U. S. Department of Agriculture, Washington, D. C., November 25, 1917.

the results of this work, we will attempt in this communication to present the most significant indications as to the value of the test for asphalt content. We may divide the selected tests into three groups as follows:

1. Residual petroleums, asphaltic petroleums, and oil asphalt cut-backs having different specific gravities and consistencies;

2. A series of Mexican products having specific gravities ranging from 0.935 to 1.024 and specific viscosities at 100° C. ranging from 2.4 to 131.0 and a series of Mexican products having specific gravities ranging from 0.935 to 0.965, with specific viscosities at 25° C. ranging from 20.4 to 165.0, and with flash points ranging from 42 to 105;

TABLE I.—COMPARISON OF TESTS MADE ON MEXICAN OILS WITH TESTS MADE ON OILS FROM OTHER SOURCES.

Type of Oil.	Specific Gravity.	Specific Viscosity.		Time Heated at 249 to 260°C., min.	Percentage of Residue.	Penetration of Residue.
		At 25° C.	At 100° C.			
Mexican	0.965	165.0	....	45	59.5	100
Texas	0.940	163.6	....	95	69.1	100
Mexican	0.943	94.8	....	35	64.2	97
Mid-Continent	1.031	99.0	....	50	54.4	102
Mexican	1.004	....	24.4	45	78.4	103
Trinidad	1.004	....	29.1	90	83.6	103
Mexican	0.991	....	16.8	30	78.0	97
California	0.994	....	17.0	120	76.4	100

3. A selected sample upon which numerous tests were made to discover effects, if any, that varying conditions might have upon the results.

In all the tests with the exception of those under No. 1, it was desired to obtain a residue that would yield a penetration of 100.

Group No. 1 Tests.—In the tests of group No. 1, it was found that no general relation could be discovered between the percentage of asphalt and ordinary test characteristics of the sample. The source of the oil has a great influence on the results of the test: for instance, two oils from different sources when heated for the same length of time will give entirely different amounts of residue, notwithstanding the fact that they have practically the same consistency or specific gravity; and

when these samples have been heated until the residues show the same penetration they do not necessarily have the same percentage of residue. This was shown when tests of Mexican oils were compared with tests of other oils. Some typical results are given in Table I.

A comparison of the Mexican product with the Texas product shows that when the samples had been heated until they gave the same penetration, the difference in the percentage of their residues was 9.6. A comparison of the Mexican product

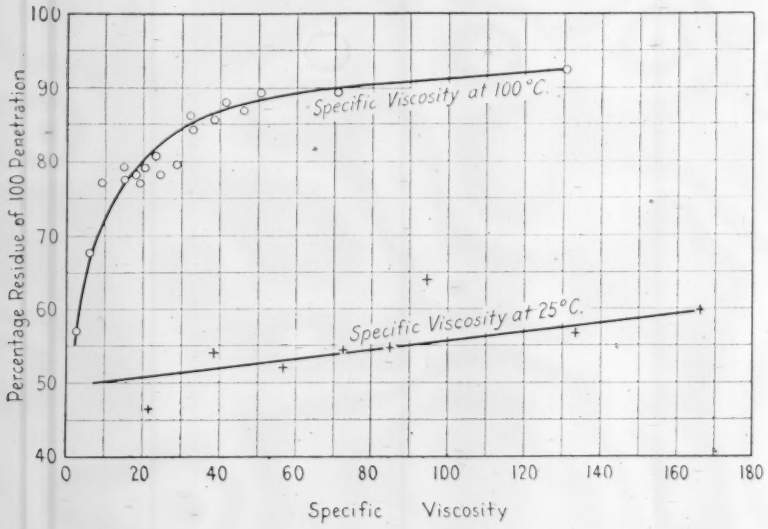


FIG. 1.—The Asphalt Contents of Mexican Road Oils.

with the Trinidad product shows that when the samples had been heated until they gave the same penetration, the difference in the percentage of their residues was 5.2. With the Mid-Continent residual it is shown that a much lower percentage of asphalt results, although the original oil was slightly heavier, and the residue somewhat softer. In the last case, a comparison of the Mexican product with the California product shows that there was only a slight difference in the percentage of their residues. It may be especially noted that the evaporation took place much more rapidly with the Mexican samples, and it

necessarily required a shorter time to gain residues yielding a penetration of approximately 100 with such oils.

Group No. 2 Tests.—The results of tests made on materials stated under group No. 2 are given in Table II. Generally speaking, it was found that an approximate relation exists between the percentage of residue of 100 penetration and between

TABLE II.—PERCENTAGE OF RESIDUE OF MEXICAN OILS.

Serial No.	Specific Gravity.	Specific Viscosity.	Percentage Insoluble in 86° B. Naphtha.	Flash Point, deg. Cent.	Percentage of Residue.	Penetration of Residue.
			SPECIFIC VISCOSITY AT 100° C.			
14104	0.935	2.4	13.8	70	56.8[a]	100
14044	0.961	6.2	17.5	98	67.6	78
12027	0.995	19.8	19.6	95	77.0	90
10460	0.990	9.4	17.3	100	77.2	91
10491	0.991	16.8	19.4	60	78.0	97
11147	0.995	17.5	20.1	..	78.0	95
10477	0.996	18.6	18.6	75	78.4	99
11164	1.004	24.4	20.4	..	78.4	102
10475	0.993	15.7	19.4	70	79.0	97
11154	1.005	20.6	17.3	..	79.2	98
11630	1.001	29.1	20.6	..	79.6	100
11093	1.002	22.5	....	..	80.6	100
10500	1.013	32.5	....	..	84.4	100
14106	0.991	38.7	20.0	206	85.8	100
14045	1.004	32.3	22.0	190	86.2	102
14126	0.998	46.0	....	204	87.2	92
12326	0.999	41.6	20.9	..	87.8	100
12392	1.008	51.7	....	..	89.0[a]	100
10266	1.015	70.9	21.7	..	89.3[a]	100
12413	1.024	131.0	22.8	..	92.4[a]	100
			SPECIFIC VISCOSITY AT 25° C.			
10636	0.936	20.4	....	..	46.6	97
14042	0.954	57.0	13.3	100	52.4	80
12026	0.943	38.6	13.1	45	54.2	90
14043	0.938	72.9	13.3	100	54.4	87
12391	0.936	85.0	13.4	105	54.8	105
14104	0.935	133.8	13.8	70	56.8[a]	100
11810	0.965	165.0	16.0	65	59.5[a]	100
11766	0.943	94.8	14.3	42	64.2	97

[a] Interpolated from results of two tests—one having a slightly higher residue and the other a slightly lower residue.

the consistency, the specific gravity, the flash point, and the percentage insoluble in 86° B. naphtha. Of these relations the one involving the consistency of the material is probably the best aid in estimating the asphalt content of an oil. From the plot between the percentage of asphalt and the specific viscosity shown in Fig. 1, however, it will be noted that an estimate of the

percentage of asphalt of 100 penetration can be made only within rather wide limits.

Thus, judging from this graph, the percentage necessary to be volatilized from a sample having a specific viscosity at 100° C. ranging up to 60 may be inferred within not less than three per cent.

Group No. 3 Tests.—In group No. 3, the material selected was a Mexican asphalt having an original penetration of 177. First, six samples were taken and tested in the regular way.

TABLE III.—TESTS MADE TO NOTE RESULTS FROM HEATING DIFFERENT LENGTHS OF TIME.

Mexican Asphalt. Sample No.	Time, Heated at 249 to 260° C., min.	Percentage of Residue.	Penetration of Residue.
1	5	99.6	150
3	15	97.6	133
2	10	97.2	129
5	25	96.4	105
4	20	96.0	100
6	30	95.2	96
EFFECT OF REHEATING SAMPLES NOS. 2 AND 3.			
2	10	97.2	129
	5 additional	96.0	100
	5 additional	95.0	89
3	15	97.6	133
	5 additional	96.4	102
EFFECT OF STIRRING.			
7[a]	20	97.6	120
	5 additional	96.4	104
8[b]	20	97.0	114

[a]Stirred very frequently.
[b]Stirred continuously.

The first sample was heated for five minutes at the required temperature (249 to 260° C.) and each successive sample was heated five minutes longer than the preceding one. Samples Nos. 2 and 3 were reheated at the required temperature. Then two additional samples, Nos. 7 and 8, were heated for twenty minutes at the required temperature, No. 7 being stirred very frequently and No. 8 continuously. Penetration tests were made on the residues from the above samples with the results shown in Table III. It will be noted that the loss is not proportional to the time of heating. If the test made on sample No. 4 is

compared with that made on sample No. 2, it will be seen that a residue of 96.0 per cent gave a penetration of 100 and that when sample No. 2 was reheated for five minutes at the required temperature a residue of 96.0 per cent was obtained, also yielding a penetration of 100. Again, if the tests made on samples Nos. 3, 5, and 7 are compared it will be seen that their final residues are the same (96.4 per cent) although sample No. 3 was reheated and sample No. 7 was both reheated and subjected to excessive stirring. The penetration tests on these residues showed a maximum difference of only three points. This would seem to indicate that intermittent heating or increased stirring did not affect the results to any great extent, although it must be conceded that results with such a viscous material, and having such low losses, are not conclusive as applied to fluid road oils.

CONCLUSIONS.

As a result of the work carried out as above described, certain conclusions are suggested to us:

1. That with a given type of oil, the consistency will indicate the percentage of asphalt;

2. That the time necessary to secure the required residue will vary within wide limits, and cannot be readily estimated while making the test as described;

3. That the effect of stirring is indicated to be less than that of other factors difficult to control, which affect the results.

There are many features of the test which may be adversely criticized. Among these may be enumerated the following: The tedious and long continued attention necessary to secure even approximate results; the difficulty in maintaining the required temperature, which is of great importance to secure concordant results; the fact that the changes taking place during heating are not understood and probably not indicative of the changes in the oil while in service on the road. At best it is a "cut and try" method, and therefore cannot be based on scientific principles of testing.

Summarizing our conclusions, it may be stated that it is our belief that the percentage of asphalt gives no additional information on the suitability of a road oil for a given purpose, which is not adequately shown by the results of other tests, better understood and at the present time well standardized.

DISCUSSION.

Mr. Smith. MR. F. P. SMITH.—We are indebted to Mr. Anderton for bringing these facts to our attention and correlating them in such shape that the relation between the specific viscosity and gravity and the percentage of residue can readily be observed. It appears to me, however, that the conclusions in the summary are not altogether justified from the work done.

As I understand the paper, Messrs. Anderton and Taylor state positively that, with a given type of oil, the consistency will indicate the percentage of asphalt, and that that being the case, together with certain other reasons, they conclude it is unnecessary to make the test known as "asphalt content." Take, however, the case of an engineer who is purchasing road oil for use on his road; he has no guarantee whatever that the material which is supplied to him will be made from a single crude; it may be made from a mixture of crude oils, some of which may yield a residue on evaporation in the road bed which has a binding value and is of use in forming a mat, while others may have very little binding or cementing value and be almost worthless as a mat-producing oil. Under those conditions, it seems to me that it is absolutely essential, for the protection of the highway engineer, that he should have some test which will determine the quantity of residue which will be left by the evaporation of the oil after it is applied to the road bed, and second, that he should examine the residue so as to determine whether or not it is possessed of sufficient binding and cementing value to make it useful for the purpose intended. I fail to see how any conclusions can be drawn from specific viscosity, gravity or any other test that we now have which will give the information that an asphalt content test, so-called, will give if it is carried sufficiently far and conducted properly, with due precaution.

There is no doubt but that the residues obtained by quick evaporation in the laboratory will differ somewhat in nature from those which result from slow evaporation after the oil has been applied to the road bed; but it is nevertheless a fact that

road oils prepared from what are termed asphaltic crudes of good quality do exhibit certain characteristics in the asphalt content that are not found in asphalt contents prepared from oils which are lacking in cementing value and have very low binding power. For that reason it is my belief that it would be extremely unwise for highway engineers to abandon the so-called asphalt-content test and the examination of the residues obtained by that test. There are a number of instances in which the asphalt-content test is carried down only until the residue has a penetration of 100. I believe that in order to get the greatest possible amount of information from this test, the evaporation should be carried not only to 100 but also a separate, or, if desired, a subsequent evaporation should be carried on until the residue has a penetration of 50, and that an examination of certain of the physical properties, notably the ductility and perhaps the fixed carbon content of both of these residues, will give information of much value which can be obtained from no other tests at present in existence. **Mr. Smith.**

MR. PRÉVOST HUBBARD.—I agree, in a measure, with both Mr. Anderton's conclusions and the statements made by Mr. Smith, but there is one point I should like to bring out in connection with the determination of asphalt content which may not have been made absolutely clear. At the present time a great many road oils are specified on the basis of their asphalt content without reference to their consistency. Now, of the two, I believe that the original consistency is a much better indication of the value of a road oil for a given purpose than a knowledge of its asphalt content. For that reason, I do not think that the asphalt content requirement should replace the consistency requirement in specifications. It appears to me that the asphalt-content determination is of much more value to the investigator as a means of ascertaining the character of the crude from which the road oil has been obtained than for actually determining the value of that oil for a given purpose, for the reason, that as Mr. Smith said, an oil that will show a high percentage of asphalt under the test for asphalt content may not develop that asphalt after application. It seems to me that a much more rational test to include in specifications would be the consistency of the residue obtained after the oil has been **Mr. Hubbard.**

Mr. Hubbard. subjected to a moderate evaporation test, rather than a necessarily high evaporation test which creates conditions entirely foreign to those met with in service.

Mr. Smith. MR. SMITH.—I heartily agree with Mr. Hubbard. I should be sorry if anybody had interpreted my remarks to mean that I believe that with the asphalt-content test it was unnecessary to make the other tests that Mr. Hubbard has referred to. Personally I regard them as being all vitally necessary and essential at this stage of our knowledge of road oil.

Mr. Gage. MR. R. B. GAGE.—Looking at this subject from another viewpoint, we find there are other things to be considered than simply the technical part of specifications for a road oil.

If we were to purchase oils only under consistency tests as determined by the viscosity, it would be possible to secure two oils of the same consistency with different asphaltic contents when both are reduced to a given penetration. Since the value of an oil in general depends upon its asphaltic content—for there is little binding power in an oil until it has cured on the road—it naturally follows that the larger the asphaltic content of an oil the greater binding power it has.

Again, if a given quantity of asphaltic binder is required per unit of surface, a smaller quantity will be required of an oil such as a "cut-back" containing 50 to 60 per cent of asphaltic residue, than of an oil which contains only 40 to 50 per cent of residue, even if the consistency of the two oils is the same. A few years ago the price of "cut-back" oils was considerably in excess of ordinary topped crude or road oil, but the demand for the latter product has become so great since it has been adopted for fuel purposes, that this difference in price no longer exists; and when the prices of the two products are compared on their asphaltic contents, it is sometimes found that the "cut-back" is the cheaper per gallon, to say nothing of the results secured by the two different materials when applied.

There is also a big difference in the residues of different oils when reduced to a given penetration and if we were to accept or reject oils on the consistency test only, it would not be possible to differentiate between oils containing different character residues. Some oils will give a residue that is ductile and very desirable for road repairs, while other oils appear to give residues

that are more or less of a lubricating nature and do not have the characteristics or produce the same results as residues of a more ductile nature. The oils of the non-ductile type appear to have a greater absorbing power than those of the ductile type and often absorb more material than they have power to hold properly in place. Mr. Gage.

Personally, I think it would be a mistake in preparing specifications for the purchase of road oils, not to include some tests that define the character of the oils when reduced to a given penetration, for the character of the residue is just as important, or often more so, than the consistency of the oil or its so-called asphaltic content.

If the character of the residues is the same, the price of these materials could then be based directly upon their asphaltic content, which would be a fairer way of judging them than by the price per gallon, without specifying a given asphaltic content.

MR. B. A. ANDERTON.—It was not our intention to conclude that consistency tests alone should be used in place of tests for asphalt content, but that, judging from the results of these tests, it would seem that a combination of certain other tests—the consistency at normal temperature, naphtha insoluble, specific gravity, etc., together with the volatilization test at 163° C. and the consistency of the residue—might be utilized for the proper selection of oils without the use of the asphalt content test, a determination which seemed to us to be so susceptible to inaccuracies that its results would not give a measure of the qualities of oils with the same degree of certainty as combinations of other tests which are at present well standardized and well understood. Mr. Anderton.

THE USES AND PROPERTIES OF WATER-RESISTANT PLYWOOD.

By Armin Elmendorf.

The uses of plywood may be put into two broad classes: one in which appearance or finish is the prime consideration and strength is secondary, the other in which strength is primary and appearance is secondary. A 3-ply door panel would be a typical example of the first class and a bulkhead in an airplane fuselage of the second. Practically all plywood in furniture belongs to the first class, where it has been known under various names as veneer, veneer panel, and plywood.

On account of the frequent confusion arising from the ambiguous use of the terms "veneer" and "plywood," manufacturers are now beginning to standardize the terminology. "Veneer" is being limited to the individual thin sheets of wood cut on various types of veneer machines. "Plywood" refers to the combination of several sheets of veneer glued together usually so that the grain of one ply crosses that of the adjacent plies at 90 degrees.

The production of plywood for furniture and interior decoration still greatly exceeds that for structural parts in which the mechanical properties are more important than the appearance of the grain. The latter field is, however, growing rapidly with the increase and spread of information relating to strength. The present paper is limited to a discussion of the uses of plywood in this field and the results of tests made to determine its mechanical properties.

Plywood is now frequently spoken of as a structural or engineering material and at least one firm confines its entire output to supplying the demands of such industries as desire the material for its strength and stiffness.

Uses of Plywood as a Structural Material.

In addition to many minor demands, there are four large industries now demanding plywood because of its mechanical

properties. They are the automobile, airplane, car, and ship-building industries. A typical use of plywood in automobile body construction is shown in Fig. 1, illustrating a molded 3-ply automobile roof. Other automobile parts extensively made of plywood are sides of commercial bodies, cab tops, dash boards, instrument boards, frames of windows, disc wheels, and door linings.

Airplane fuselages of certain types are almost entirely made

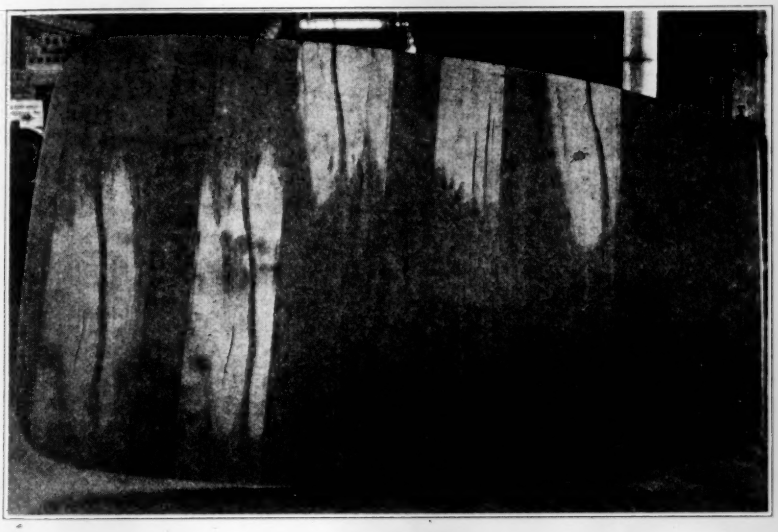


FIG. 1.—Automobile Roof Made of Molded Plywood.

of plywood. A fuselage of this kind is shown in Fig. 2. The shell or covering is reinforced both longitudinally and laterally; the longitudinal reinforcing is made of ordinary straight-grained wood but lateral reinforcing is obtained from plywood bulkheads. Such bulkheads may consist of as many as 17 plies. The supports for the motor, gusset plates, flooring, webs of the wing ribs, cheek pieces of box-section wing beams, leading edges, and center panels in some types of wings are likewise built of plywood.

EFFECT OF THE WAR ON THE DEVELOPMENT OF WATER-RESISTANT PLYWOOD.

Prior to the European War the use of plywood as an engineering material was limited to structural parts not exposed to the weather, because the glues used were quite soluble in water. With the war and the sudden demand for airplanes there also came the demand for a grade of plywood which would withstand the severest weather conditions without disintegration, which possessed great strength per unit of weight, and which could be obtained in large thin sheets. The rapid perfection of

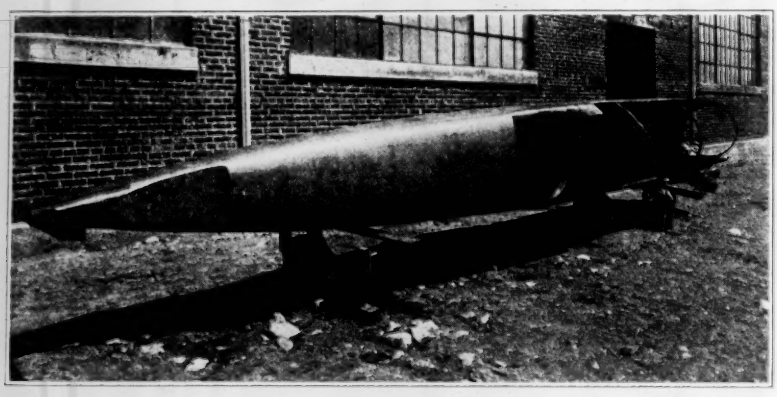


FIG. 2.—Airplane Fuselage Made of Molded Plywood.

water-resistant glues soon after our entry in the war enabled the Government to draw up specifications requiring that plywood for use in airplane construction must withstand at least eight hours of boiling or ten days of soaking in water without separation of the plies.

At the close of the war the highly water-resistant quality of the airplane grade of plywood was recognized by other industries, and the range of its applications was rapidly extended.

The Forest Products Laboratory of the U. S. Forest Service, Madison, Wisconsin, was called upon early in the war to conduct the necessary tests to supply the data needed by army and navy airplane designers. A corps of engineers and laboratory assistants was employed and tests were begun in the fall of 1917. Valu-

able data soon became available. Several months prior to the close of the war, about 35,000 tests had been made covering many variables.

The tests conducted by the Government were supplemented by the work done at such private research laboratories as that maintained by the Haskelite Manufacturing Corporation where extensive tests were made upon many structural parts made of this material. The moldability of plywood was also investigated by this company.

THE PROPERTIES OF WOOD IN THEIR RELATION TO PLYWOOD.

On account of the relatively low shearing strength of wood parallel to the grain, its high tensile strength can seldom be used because failure will almost invariably take place from shear. The tensile strength of wood parallel to the grain as well as its modulus of elasticity in this direction is from 18 to 20 times as high as the corresponding property at right angles to the grain. When the wood fibers are cross-banded, as in plywood, the tensile strength in one direction is slightly reduced, but in the direction at right angles to this it is greatly increased. The shear strength of plywood is consequently also greater than that of ordinary wood parallel to the grain. The crossing of the fibers increases the tensile strength across the face grain to such an extent that it is very difficult to split plywood. The shrinkage of wood parallel to the grain is practically negligible in comparison to the shrinkage across the grain. In plywood the shrinkage is negligible either parallel to or at right angles to the face grain due to the restraining action of the wood fibers extending in each of these directions.

By softening wood through steaming or boiling in water, it is readily bent around a comparatively sharp arc. In this process the outer fibers retain their original length and almost the entire deformation is that due to the shortening or upsetting of the remaining fibers. By drying the wood in the bent position, the fibers assume a permanent set. Similar bends, however, cannot be made across the grain of the wood. In plywood this limitation does not exist due to the fact that a large percentage of the fibers extends at right angles to the face grain. Plywood is, therefore, moldable in both directions—consequently moldable in double curvature.

TESTS ON PLYWOOD.

The tests made at the Forest Products Laboratory during the war are probably pioneer in the field of plywood testing. The discussion which follows relates to the work done at that institution under the direction of the writer from early fall of 1917 until the signing of the armistice.

PURPOSE.

It will be borne in mind that plywood is in many respects a new material of construction and that in order to determine its mechanical properties all the standard strength tests have to be made as well as such tests which will reveal its more unique properties. Tests were therefore undertaken to determine the following:

1. The bending, tensile, shear, and column strength, and the resistance to splitting of 3-ply plywood of about 35 species, the plies in any one panel being of the same thickness and species;
2. The laws governing the relation between the bending and shear strengths and the specific gravity of 3-ply plywood of various species;
3. The effect on the strength properties of varying the ratio of core to total panel thickness of 3-ply plywood, of using low density veneer for the core stock in combination with high density veneer for the faces, and of increasing the number of plies for a given total thickness;
4. Factors affecting the warping of plywood;
5. Shrinkage of 3-ply plywood of several species.

MATERIAL.

Inasmuch as the largest part of the veneer used in the plywood industry is cut on lathes (that is, rotary cut) the endeavor was made to obtain veneer of all common species cut by this method. Certain species such as red wood, Spanish cedar, and mahogany do not lend themselves to this method of cutting, so that veneer of these species was either sliced or sawed.

In most cases, veneer of a particular species was purchased from several firms so as to obtain data on a wide range of

material. From one to five shipments were tested for each species. Five 3-ply panels of the following thicknesses usually constituted a shipment: $\frac{3}{30}$, $\frac{3}{24}$, $\frac{3}{20}$, $\frac{3}{16}$, $\frac{3}{12}$, $\frac{3}{10}$, $\frac{3}{8}$, and $\frac{3}{6}$ in.

At the time working plans for the tests were drawn up, the use of water-resistant glues was so limited that it was decided to specify one of the common vegetable glues for all of the panels. Perkins vegetable glue was selected on account of its extensive use at that time. Subsequent strength tests showed, however,

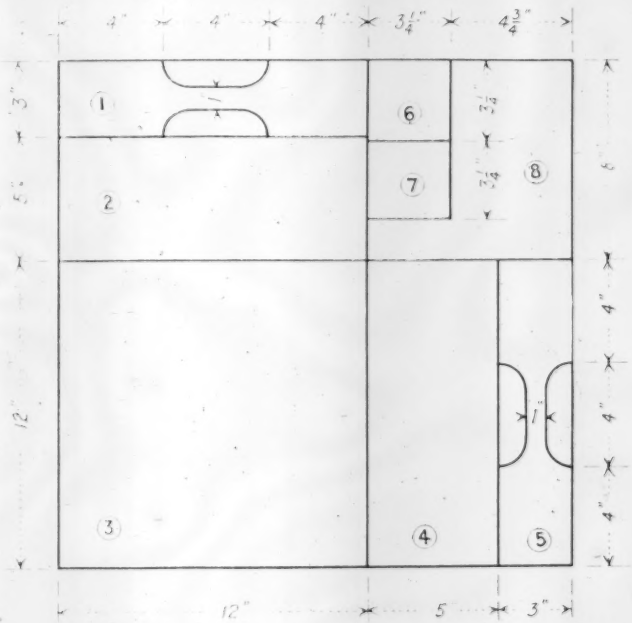


FIG. 3.—Cutting Diagram Showing Dimensions of Test Specimens.

that with the exception of the resistance to splitting and to a certain degree the shear strength, slight differences in strength of the glue had very little effect on the strength properties. The strength properties of water-resistant plywood are therefore identical with those of the material tested. It is in its industrial applications where the panels must be steamed prior to molding or where they are exposed to weathering action that water-resistant glues are imperative.

Panels were shipped to the laboratory trimmed to size, 20 by 20 in. In some cases the veneer was both cut and glued up into panels by one company, while in other instances the cutting and gluing were done by different companies. Only clear stock free from knots and checks was used. The panels were shipped to the laboratory unsanded and were tested in this condition.

DESCRIPTION OF TESTS.

The trimmed panels were cut into eight pieces as shown in Fig. 3 and the following tests were made: column-bending, tension, splitting, shear, and warping.

Column-Bending Test.—This test was made to determine the strength and stiffness of plywood in bending. Because the strength and stiffness parallel to the face grain are usually different from these properties across the face grain, it was necessary to make tests in each of these two directions. Test pieces Nos. 2 and 4, Fig. 3, were used for this purpose.

Fig. 4 shows the method of testing. The ends of the test specimens were rounded to approximately a semi-circle, and deflections were measured at the center of the column on the scale shown in the figure. The product of the load and the deflection was recorded as the bending moment.

The bending strength value termed the "column-bending modulus" was computed by adding the direct compressive stress at the maximum moment to the corresponding flexural stress using the formula:

$$S = \frac{P}{A} + \frac{6M}{bd^2}$$

where S = column-bending modulus, A = area of cross-section, P = load at maximum moment, M = maximum bending moment, b = width of test specimen, and d = the thickness of test specimen.

For test pieces $\frac{3}{8}$ in. or over in thickness, the cross-bending test was used in which the test specimen was supported at the ends on plates resting on rollers and the load was applied at the center. The standard formula for simple beams loaded at the center was used in computing the stresses for this test. Inas-

much as the strength determined in this way is practically the same as the column-bending modulus, these strength values were averaged and are given in all tables as column-bending moduli. Only the thickest stock could be tested in cross-bending because the deflections prior to failure for thinner stock were so great that the specimens would slip off the supports. Although the specimens were only 12 in. long, some of them were almost bent double before complete failure took place.

It must be observed that the column-bending modulus is not a true stress but simply a measure of the strength in bending similar to the modulus of rupture of ordinary wood. In most cases, the direct compressive stress introduced during the test is only a small fraction of the bending or flexural stress, so the column-bending modulus may be used with little error in computations similar to those involving the modulus of rupture of plain timber.

The moduli of elasticity of plywood were computed from the maximum loads obtained in the column-bending test, or for the thicker material from the cross-bending test. The following formulas were used:

$$\text{for column-bending, } E = \frac{P\,L^2}{\pi\,I};$$

$$\text{for cross-bending, } E = \frac{P'\,L^3}{48\,fI};$$

where E = modulus of elasticity of plywood in bending, P = maximum load sustained in column-bending, P' = any load within the elastic limit of the plywood in cross-bending, L = length of the plywood column or the length of the span in cross-bending, I = least moment of inertia of the cross-section of the specimen, and f = deflection corresponding to P'.

Tension Test.—Due to the great difference in the tensile strength of wood along and across the grain, the strength of plywood in tension is usually different in the two directions parallel and perpendicular to the face grain, so tension tests were made in each of these directions. Test pieces Nos. 1 and 5, Fig. 3, were used for this purpose. They were held by ordinary flat grips and tested in direct tension to rupture. The method

of testing is illustrated in Fig. 5, a speed of 0.025 in. per minute being used.

The strength value tabulated as the tensile strength was

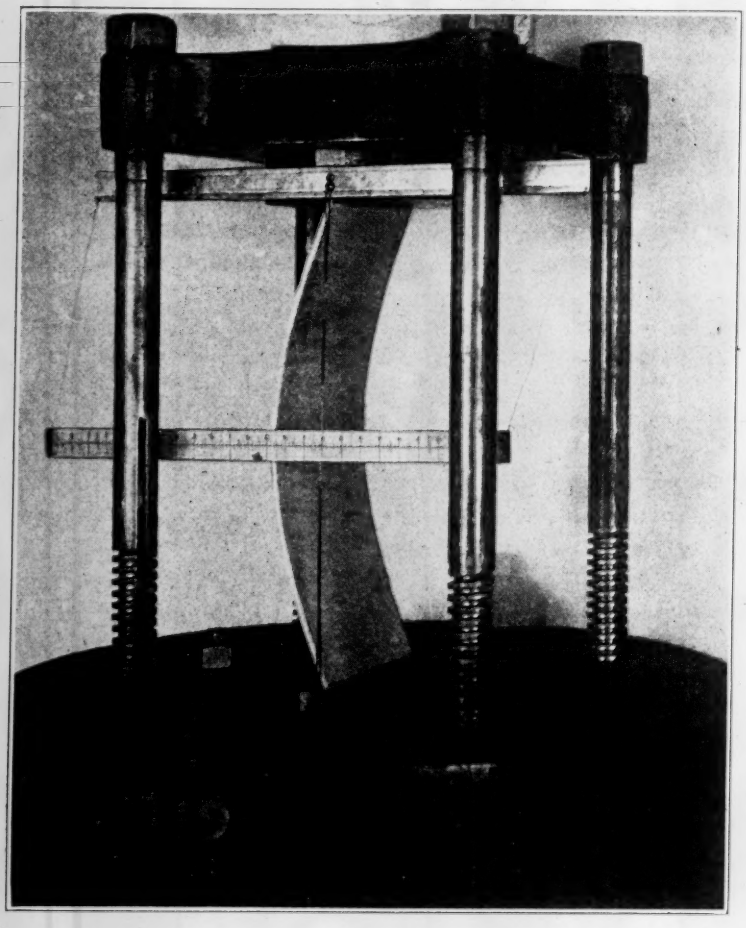


FIG. 4.—Method of Testing Plywood in Column-bending.

computed by dividing the load at rupture by the entire area at the minimum cross-section.

On account of its relatively high shearing strength, plywood

tension members are not so liable to fail in shear as ordinary wood and are therefore structurally quite feasible. The data obtained from the tests may be applied in design in computing sections of such members.

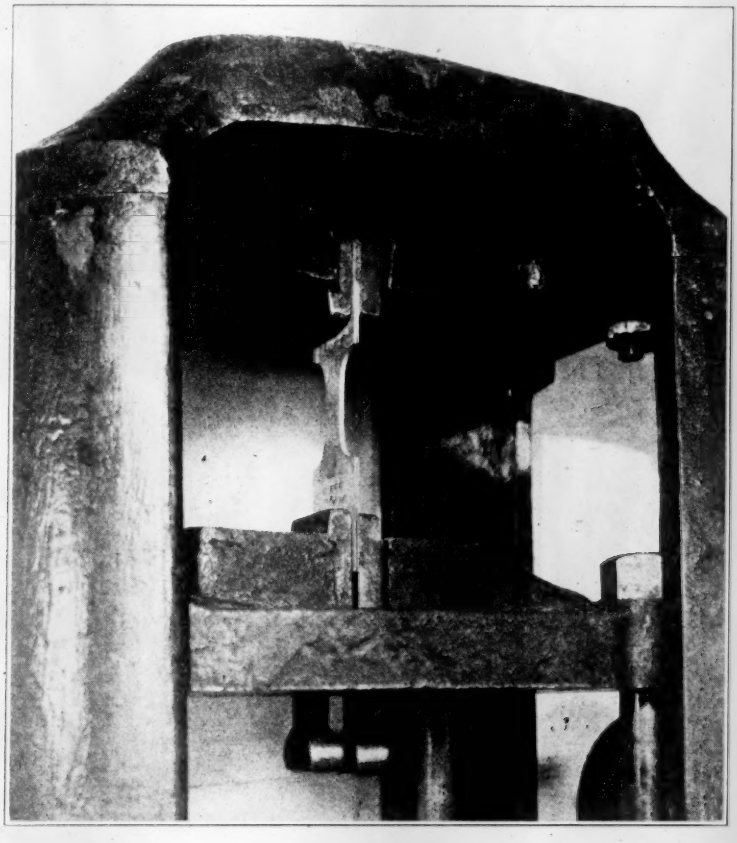


FIG. 5.—Tension Test of Plywood.

Splitting Test.—Two test specimens were used in determining the relative resistance to splitting of various plywood panels, represented by Nos. 6 and 7 in Fig. 3. They were pierced by the conical spear shown in Fig. 6. The spear is 8 in. long and 2 in. in diameter and together with the rod weighs 11.22 lb. It

FIG. 6.—Testing the Splitting Resistance of Plywood.

was first allowed to drop upon the center of the specimen from a height of $\frac{1}{2}$ in. This held the latter upon the spear. The heights of drop were then increased in increments of $\frac{1}{2}$ in. until failure due to splitting occurred.

The resistance of the material to splitting is represented by the splitting energy. This is the total work necessary to cause

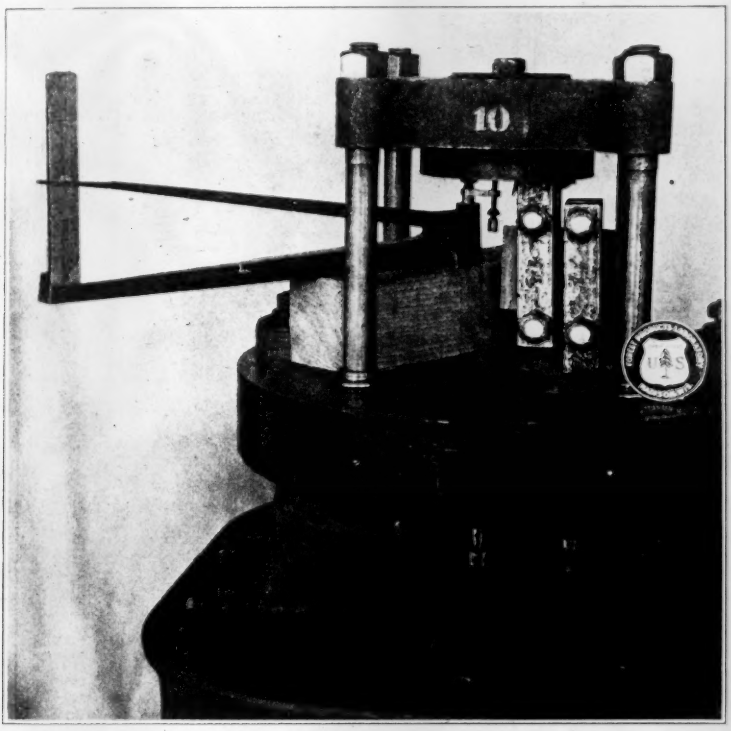
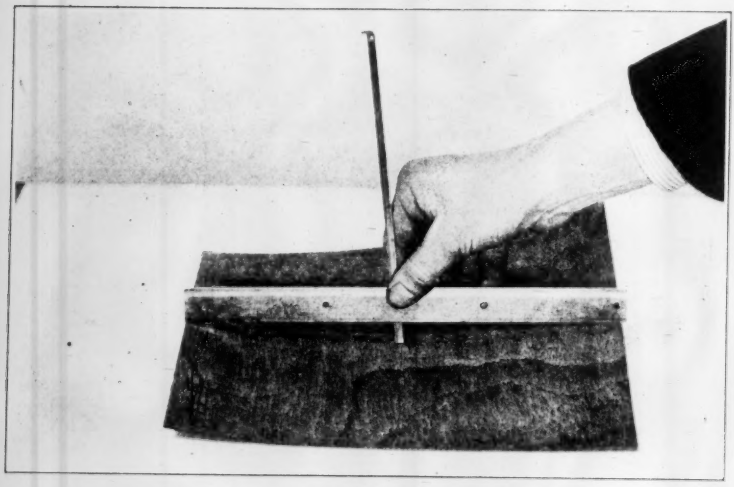
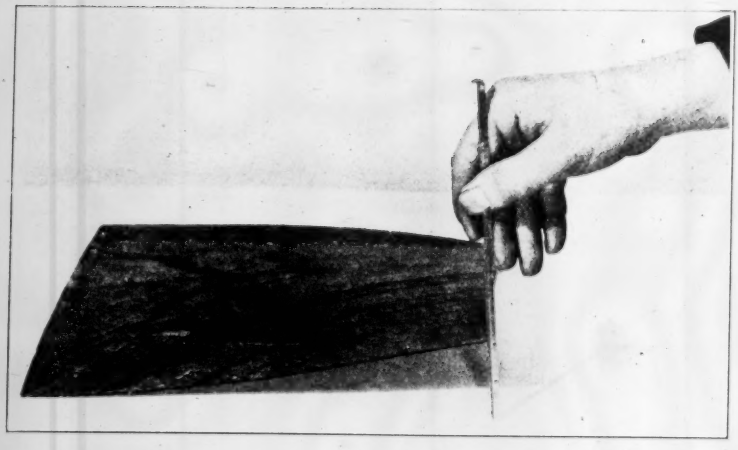


FIG. 7.—Testing the Shear Strength of Plywood with the Specimen Clamped between Steel Posts.

failure and is computed by adding together the distances through which the spear falls and multiplying by the weight of the spear and rod. The splitting energy is a strength factor that may be used in determining the relative resistances to splitting of various plywood members penetrated by screws or bolts. It is merely a factor for comparing different panels and as a numerical quantity cannot be used in design.



(*a*) Cupping.



(*b*) Twisting.

FIG. 8.—Measuring Plywood for Cupping and Twisting.

Shear Test.—Most of the shear test specimens were cut from part No. 8, Fig. 3, but in special tests in which greater lengths or widths were required or the direction of the shear forces varied, the specimens were cut from large panels made for this purpose. In most shear tests, the specimens were clamped between steel posts which were roughened on the clamping faces, as illustrated in Fig. 7. In both methods the load was applied by the moving head of the testing machine at the rate of 0.025 in. per minute.

The shear stresses given in the tables were computed by dividing the ultimate load sustained by the area of the sheared section—that is, by the product of its length and thickness.

Warping Test.—Panels 12 in. square of various species or embodying certain structural features that were to be investigated were exposed to different humidities so as to change their moisture contents and thereby introduce internal stresses. For many tests, specimen No. 3, Fig. 3, was used.

Warping was determined by the two measurements shown in Fig. 8 which were termed "twisting" and "cupping." In measuring the twist of a panel, it was placed upon a flat surface so that three corners rested on this surface and the distance from the surface to the fourth corner was measured. This height divided by the length of the edge gave the slope of the edge and therefore measured the angle through which it had been twisted relative to the opposite edge. When measuring cupping, the straight edge was placed across the center of the panel as shown in Fig. 8 and the maximum recession from the straight edge was measured.

Shrinkage and Expansion Tests.—Tests to determine the change of dimension with changing moisture content were only made on very thin plywood. Material of this kind was being considered for airplane usage and data on shrinkage were desired. It seems reasonable to believe, however, that the results obtained should also apply to thicker stock of the same species and ratio of ply thicknesses. Total shrinkage measurements from the soaked to the oven-dry condition were, however, made on numerous thicker plywood samples.

The moisture content of the thin test sheets was raised by exposing them to relative atmospheric humidities ranging from 95 to 100 per cent at temperatures of from 80 to 85° F.

TABLE I.—STRENGTH OF VARIOUS SPECIES OF 3-PLY PANELS.

All plies in any one panel were of the same thickness and of the same species—grain of successive plies at right angles.

In most cases eight thicknesses of plywood, ranging from $\frac{3}{30}$ in., to $\frac{3}{6}$ in., were tested.

Species.	Average Specific Gravity of Plywood Based on Oven-Dry Weight and Volume at Test.	Average Moisture, per cent.	Column Bending.						Tension Tests.				Splitting Resistance.	
			Column-Bending Modulus.				Modulus of Elasticity, 1000 lb. per sq. in.		Parallel.		Perpendicular.			
			Parallel.[1]		Perpendicular.[1]									
			Number of Tests.	Strength, lb. per sq. in.	Number of Tests.	Strength, lb. per sq. in.	Parallel.	Perpendicular.	Number of Tests.	Strength, lb. per sq. in.	Number of Tests.	Strength, lb. per sq. in.	Number of Tests.	Percentage of Birch.[2]
Ash, black	0.49	9.1	120	7 760	120	1 770	1 070	96	120	6 180	120	3 940	240	73
Ash, commercial white	0.60	10.2	200	9 930	200	2 620	1 420	143	200	6 510	200	4 350	400	71
Basswood	0.42	9.2	200	7 120	200	1 670	1 210	85	200	6 880	200	4 300	400	63
Beech	0.67	8.6	120	15 390	120	2 950	2 150	167	120	13 000	120	7 290	240	94
Birch, yellow	0.67	8.5	195	16 000	200	3 200	2 260	197	200	13 210	200	7 700	400	100
Cedar, Spanish	0.41	13.3	115	6 460	115	1 480	1 030	84	115	5 200	115	3 340	230	60
Cherry (probably black cherry)	0.56	9.1	115	12 260	115	2 620	1 630	152	115	8 460	115	5 920	230	80
Chestnut	0.43	11.7	40	5 160	40	1 110	740	75	40	4 430	40	2 600	80	74
Cottonwood (probably common)	0.46	8.8	120	8 460	120	1 870	1 440	109	120	7 280	120	4 240	240	85
Cypress, bald	0.45	8.0	113	8 890	113	1 850	1 220	95	113	6 160	113	3 980	148	49
Douglas fir (coast type)	0.48	8.6	176	9 340	200	1 940	1 530	126	200	6 188	200	3 910	374	63
Elm, cork	0.62	9.4	65	12 710	65	2 500	1 980	136	65	8 440	65	5 500	130	99
Elm, white	0.52	8.9	160	8 680	160	1 970	1 220	109	160	5 860	160	3 990	320	75
Fir, true (probably white fir)	0.40	8.5	24	9 200	24	1 811	1 580	100	24	5 670	24	3 770	48	60
Gum (probably black gum)	0.54	10.6	40	8 090	40	1 920	1 280	113	35	6 960	35	4 320	70	55
Gum, cotton	0.50	10.3	80	7 760	80	1 580	1 300	111	80	6 260	80	3 760	160	60
Gum, red	0.54	8.7	182	9 970	182	2 070	1 590	120	182	7 850	182	4 930	364	80
Hackberry	0.54	10.2	80	8 100	80	1 880	1 150	99	80	6 920	80	4 020	160	84
Hemlock, western	0.47	9.7	119	9 250	119	1 960	1 580	112	119	6 800	119	4 580	238	63
Magnolia (probably evergreen)	0.58	8.8	80	10 830	80	2 600	1 700	138	80	9 220	80	5 730	120	85
Mahogany, African (probably Khaya species)	0.52	12.7	20	8 070	20	2 000	1 260	114	20	5 370	20	3 770	...	..
Mahogany, Philippine (probably tanguile)	0.53	10.7	25	10 160	25	2 310	1 820	169	25	10 670	25	5 990	50	90
Mahogany, true	0.48	11.4	35	8 500	35	1 940	1 250	117	35	6 390	35	3 780		
Maple, soft (probably silver maple)	0.57	8.9	120	11 540	120	2 420	1 750	145	120	8 180	120	5 380	240	106
Maple, hard (sugar or black maple)	0.68	8.0	202	15 600	202	3 340	2 110	189	192	10 190	202	6 530	404	114
Oak, commercial red	0.59	9.3	115	8 500	115	2 070	1 290	120	115	5 480	115	3 610	230	70
Oak, commercial white	0.64	9.5	195	10 490	195	2 310	1 340	118	195	6 730	195	4 200	390	85
Pine, sugar	0.42	9.4	65	8 050	70	1 670	1 310	90	70	5 430	70	3 690	140	47
Pine, white	0.42	5.4	40	10 130	40	2 050	1 570	111	40	5 720	40	3 340	80	31
Poplar, yellow	0.50	9.4	165	8 860	165	1 920	1 540	115	155	7 390	165	4 720	330	51
Redwood	0.42	9.7	105	8 230	105	1 550	1 180	108	105	4 770	105	2 960	210	48
Spruce, Sitka	0.42	8.3	121	7 710	121	1 690	1 370	105	121	5 650	121	3 410	224	78
Sycamore	0.56	9.2	163	11 040	163	2 340	1 630	130	163	8 030	163	5 220	326	77
Walnut, black	0.59	9.1	110	12 660	110	2 770	1 740	141	110	8 250	110	5 260	220	77
Yucca species	0.49	7.3	33	2 960	33	900	560	44	33	2 210	33	1 700	66	14

[1] Parallel and perpendicular refer to the direction of the grain of the faces relative to the direction of the application of the force.

[2] The relative splitting resistance of the various panels tested depends largely on the holding strength of glue.

NOTE.—In some of the species listed above the tests are rather limited in number. Since there is considerable variation in the strength of wood, further tests on additional material would be expected to modify the values appreciably in some cases.

THE PROPERTIES OF PLYWOOD AS REVEALED BY THE TESTS.

In all strength tests on wood made at the Forest Products Laboratory, the moisture in the wood and the specific gravity of the test specimen are determined. Without a knowledge of these factors no positive statement can be made about the strength of any species. By a large reduction in moisture, for example, the strength of a structural member of wood may be doubled. By selection for density, two timbers of the same species may be obtained, one of which is twice as strong as the other. From this it will be seen that it is imperative to know both the moisture and the specific gravity for each strength value. The same is true for plywood. Both of these factors were determined in each strength test.

For many uses, as for example in airplanes, maximum bending strength or maximum stiffness per unit of weight are desired. By applying the laws of mechanics to the data following, superior constructions may frequently be determined.

Bending Strength of 3-Ply Plywood of Various Species.—The column-bending moduli both parallel and across the face grain for 35 species are listed in Table I. Numerous other species not listed are cut out into veneer but the amount is inconsequential. It is believed that the species tested cover all that are of any commercial importance. Comparison of the column-bending moduli parallel and across the face grain shows that on the average the bending strength in the former direction is about 4.5 times as great as in the latter direction, when all plies in a 3-ply panel are of the same thickness and species.

Stiffness of 3-Ply Plywood of Various Species.—The moduli of elasticity of 3-ply plywood given in Table I show that in general the stiffness of 3-ply plywood, in which all plies are of the same thickness and species, parallel to the face grain is practically the same as that of ordinary wood. The modulus of elasticity across the face grain is however considerably less than in the parallel direction. The latter may be from 9 to 15 times as great as the former.

Tensile Strength of 3-Ply Plywood of Various Species.—The tensile strength values listed in Table I are based upon the entire cross-sectional area. By far the largest part of the load

TABLE II.—TENSILE STRENGTH OF PLYWOOD AND VENEER.

Species.	Number of Tests.	Moisture at Test, per cent.	Specific Gravity[1] of Plywood.	Tensile Strength[2] of Three-ply Wood Parallel to Grain of Faces, lb. per sq. in.	Tensile Strength[3] of Single-ply Veneer $1\frac{1}{4}$ (*d*), lb. per sq. in.
	(*a*)	(*b*)	(*c*)	(*d*)	(*e*)
Ash, black	120	9.1	0.49	6 180	9 270
Ash, commercial white	200	10.2	0.60	6 510	9 760
Basswood	200	9.2	0.42	6 880	10 320
Beech	120	8.6	0.67	13 000	19 500
Birch, yellow	200	8.5	0.67	13 210	19 820
Cedar, Spanish	115	13.3	0.41	5 200	7 800
Cherry (probably black cherry)	115	9.1	0.56	8 460	12 690
Chestnut	40	11.7	0.43	4 430	6 640
Cottonwood (probably common)	120	8.8	0.46	7 280	10 920
Cypress, bald	113	8.0	0.45	6 160	9 240
Douglas fir (coast type)	200	8.6	0.48	6 180	9 270
Elm, cork	65	9.4	0.62	8 440	12 660
Elm, white	160	8.9	0.52	5 860	8 790
Fir, true (probably white fir)	24	8.5	0.40	5 670	8 510
Gum (probably black gum)	35	10.6	0.54	6 960	10 440
Gum, cotton	80	10.3	0.50	6 260	9 390
Gum, red	182	8.7	0.54	7 850	11 780
Hackberry	80	10.2	0.54	6 920	10 380
Hemlock, western	119	9.7	0.47	6 800	10 200
Magnolia (probably evergreen)	80	8.8	0.58	9 220	13 830
Mahogany, African (probably Khaya species)	20	12.7	0.52	5 370	8 060
Mahogany, Philippine (probably tanguile)	25	10.7	0.53	10 670	16 000
Mahogany, true	35	11.4	0.48	6 390	9 580
Maple, soft (probably silver maple)	120	8.9	0.57	8 180	12 270
Maple, hard (sugar or black)	192	8.0	0.68	10 190	15 290
Oak, commercial red	115	9.3	0.59	5 480	8 220
Oak, commercial white	195	9.5	0.64	6 730	10 100
Pine, sugar	110	8.0	0.42	5 530	8 300
Pine, white	40	5.4	0.42	5 720	8 580
Poplar, yellow	155	9.4	0.50	7 390	11 080
Redwood	105	9.7	0.42	4 770	7 160
Spruce, Sitka	121	8.3	0.42	5 650	8 480
Sycamore	163	9.2	0.56	8 030	12 040
Walnut, black	110	9.1	0.59	8 250	12 380
Yucca species	33	7.3	0.49	2 210	3 320

Sample computation:

To obtain the tensile strength of three-ply wood consisting of 2 $\frac{1}{20}$-in. birch faces and a $\frac{1}{16}$-in. basswood core.

Parallel to face grain $= 2 \times \frac{1}{20} \times 19{,}820 = 1982$ lb. per in. of width.

Perpendicular to face grain $= 1 \times \frac{1}{16} \times 10{,}320 = 645$ lb. per in. of width.

This computation neglects the tensile strength of the ply or plies perpendicular to the grain, which is comparatively small, and the results are therefore slightly in error.

[1] Specific gravity based on oven-dry weight and volume at test.

[2] Based on total cross-sectional area.

[3] Based on assumption that center ply carries no load.

Data based on tests of three-ply panels with all plies in any one panel same thickness and species.

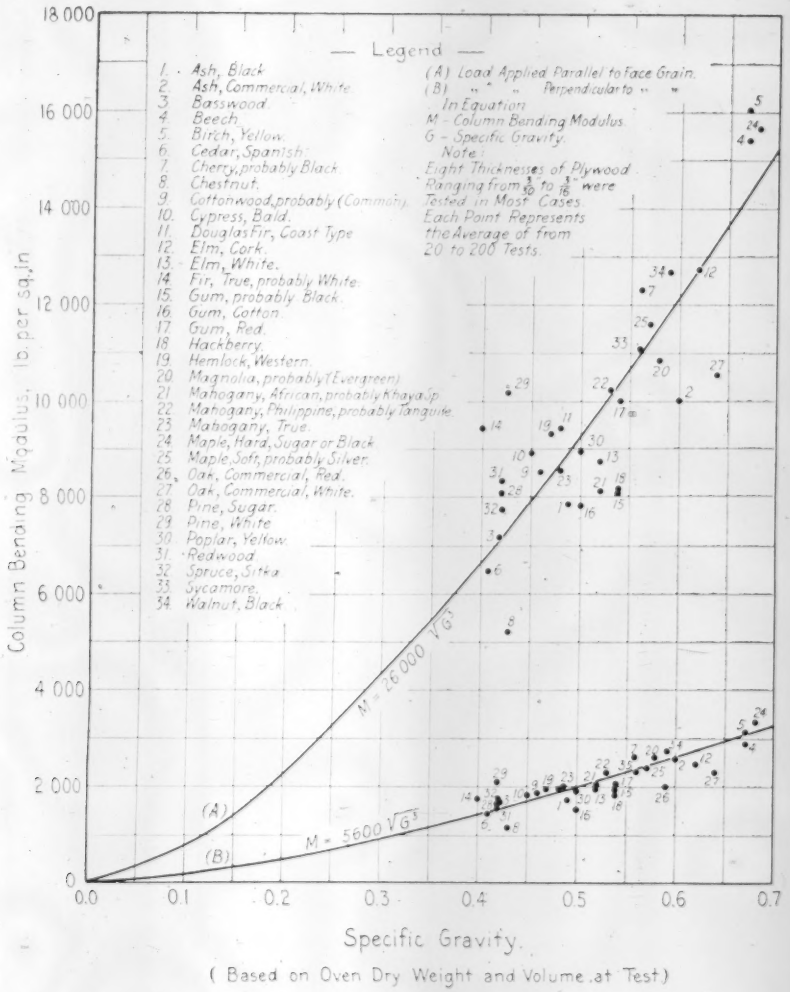


FIG. 9.—Curves Showing the Relation between Specific Gravity and the Bending Strength of 3-ply Plywood. Each Ply One-third of Total Thickness.

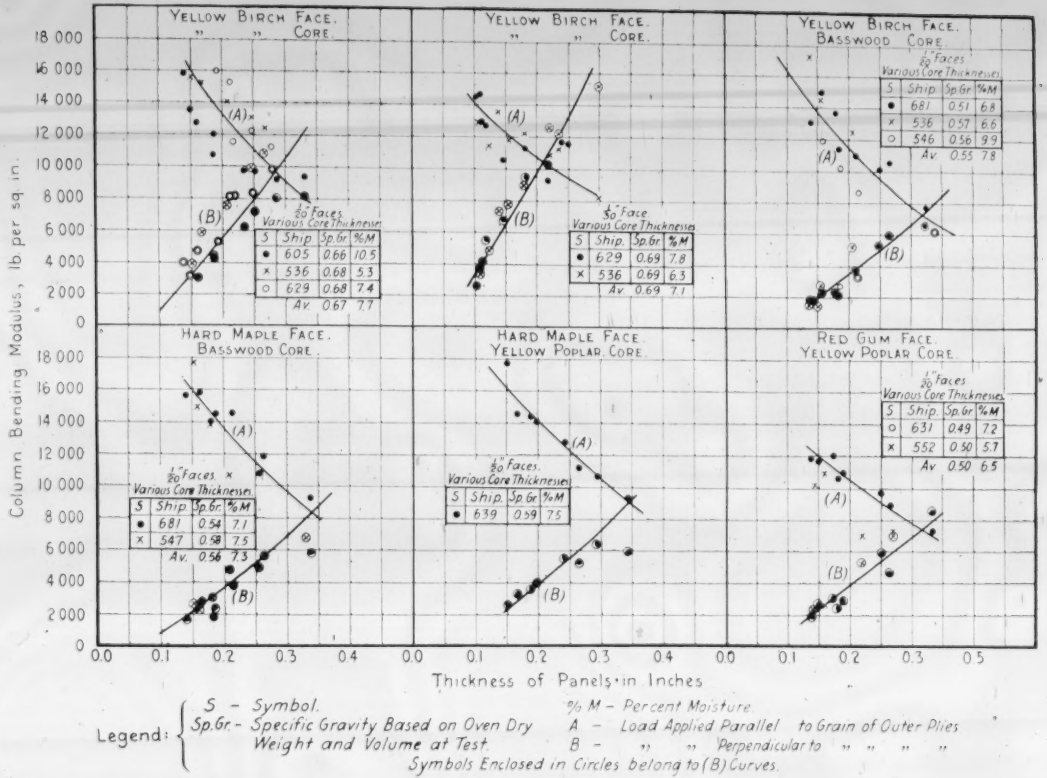

YELLOW BIRCH FACE.
" " CORE.
1/20" Faces. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
● | 605 | 0.66 | 10.5
× | 536 | 0.68 | 5.3
○ | 629 | 0.68 | 7.4
Av. 0.67 7.7
YELLOW BIRCH FACE.
" " CORE.
1/10" Face. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
● | 629 | 0.69 | 7.8
× | 536 | 0.69 | 6.3
Av. 0.69 7.1
YELLOW BIRCH FACE.
BASSWOOD CORE.
1/20" Faces. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
● | 681 | 0.51 | 6.8
× | 536 | 0.57 | 6.6
○ | 546 | 0.56 | 9.9
Av. 0.55 7.8
HARD MAPLE FACE.
BASSWOOD CORE.
1/20" Faces. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
● | 681 | 0.54 | 7.1
× | 547 | 0.58 | 7.5
Av. 0.56 7.3
HARD MAPLE FACE.
YELLOW POPLAR CORE.
1/20" Faces. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
● | 639 | 0.59 | 7.5
RED GUM FACE.
YELLOW POPLAR CORE.
1/20" Faces. Various Core Thicknesses.
S | Ship. | Sp.Gr. | %M
○ | 631 | 0.49 | 7.2
× | 552 | 0.50 | 5.7
Av. 0.50 6.5
(A)
(B)
Column Bending Modulus, lb per sq. in.
18 000
16 000
14 000
12 000
10 000
8 000
6 000
4 000
2 000
0
0.0 0.1 0.2 0.3 0.4 0.5
Thickness of Panels in Inches
Legend:
S - Symbol.
Sp.Gr - Specific Gravity Based on Oven Dry Weight and Volume at Test.
% M - Percent Moisture.
A - Load Applied Parallel to Grain of Outer Plies
B - " " Perpendicular to " " " "
Symbols Enclosed in Circles belong to (B) Curves.

FIG. 10.—Curves Showing the Relation between the Unit Bending Strength of 3-ply Plywood and Various Thicknesses, All Having the same Thickness of Face Veneer. The Length of Test Specimens, 12 in. Each Point Represents the Average of Five Tests.

is sustained, however, by the plies that have the grain extending in the direction of the tensile force.

Resistance to Splitting of 3-Ply Plywood of Various Species.—Inasmuch as resistance to splitting of a given piece of plywood has significance only when compared with other species or constructions, this strength factor is listed in Table I as the percentage of the resistance of 3-ply yellow birch plywood. The resistances to splitting cover a fixed range of thicknesses. They were averaged for each species and then converted into percentage of the resistance of birch.

Tensile Strength of Single-Ply Veneer.—If it is assumed that

TABLE III.—COMPARISON OF STRENGTH OF THREE, FIVE, SEVEN, AND NINE-PLY YELLOW BIRCH PLYWOOD.

All plies of same thickness in any one panel.

Number of Plies.	Average Specific Gravity.[1]	Average Moisture, per cent.	Range of Total Panel Thicknesses, in.	Number of Tests.	Column-bending Modulus, lb. per sq. in.		Tensile Strength, lb. per sq. in.		Ratio of Average Splitting Resistance to 3-Ply Birch of Same Thickness, per cent.
					Parallel.[2]	Perpendicular.[2]	Parallel.	Perpendicular.	
3	0.67	8.5	$\frac{3}{30}$ to $\frac{3}{6}$	195	16 000	3 200	13 210	7 700	100
5	0.66	12.3	$\frac{5}{48}$ to $\frac{5}{10}$	60	11 780	5 320	12 700	8 680	183
7	0.67	12.7	$\frac{7}{48}$ to $\frac{7}{12}$	55	11 490	6 190	11 860	9 150	235
9	0.70	18.9	$\frac{9}{48}$ to $\frac{9}{16}$	25	8 150	5 830	10 140	8 410	342

[1] Specific gravity based on oven-dry weight and volume at test.

[2] Parallel and perpendicular refer to direction of grain of faces relative to direction of application of force.

the center ply of 3-ply plywood subjected to tension in a direction parallel to the face grain carries no load, then the tensile strength of a single ply of veneer may be computed. Such tensile strength values are listed in the last column of Table II. By means of these data the tensile strength of plywood made of any number of plies and combination of species and thicknesses may be computed. A sample computation is included with the table.

Relation of Specific Gravity to the Bending Strength of 3-Ply Plywood.—The relation between the specific gravity and the column-bending modulus is shown in the curves of Fig. 9. These curves are for 3-ply plywood in which all plies of a given

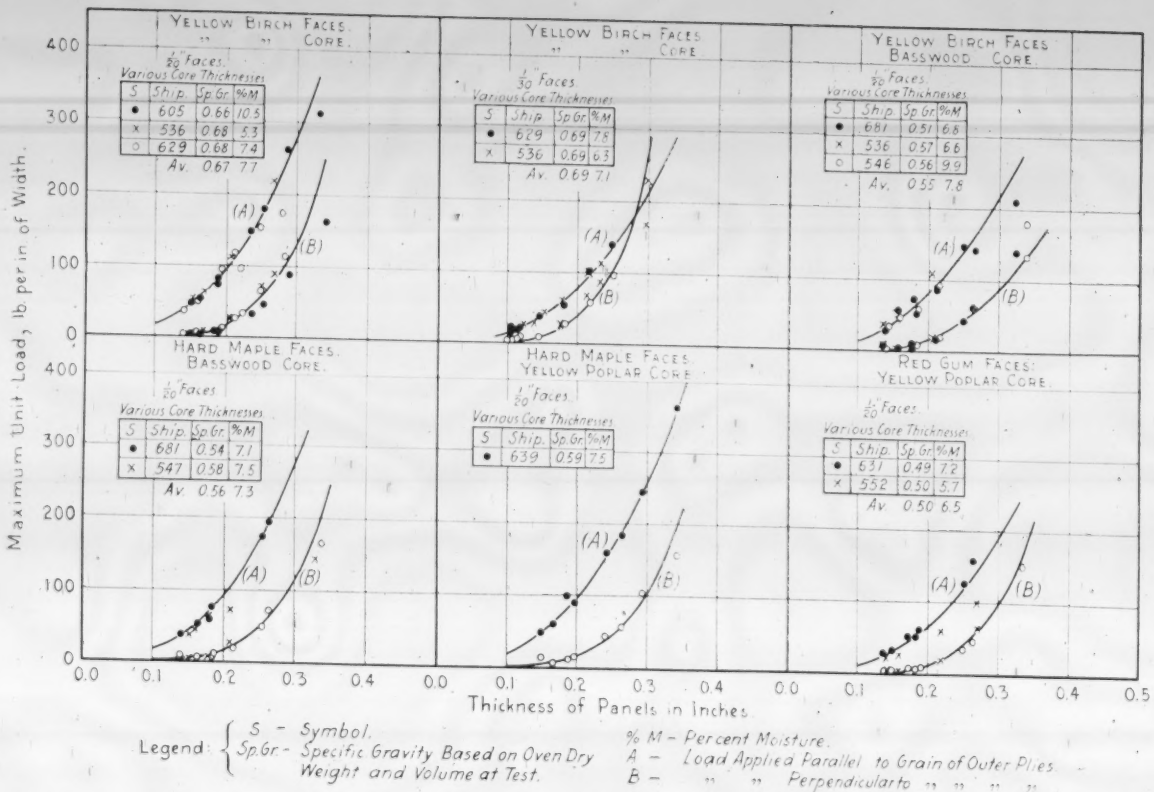

YELLOW BIRCH FACES
" " CORE
1/20" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 605 | 0.66 | 10.5
× | 536 | 0.68 | 5.3
○ | 629 | 0.68 | 7.4
Av. 0.67 7.7
YELLOW BIRCH FACES
" " CORE
1/30" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 629 | 0.69 | 7.8
× | 536 | 0.69 | 6.3
Av. 0.69 7.1
YELLOW BIRCH FACES
BASSWOOD CORE
1/20" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 681 | 0.51 | 6.6
× | 536 | 0.57 | 6.6
○ | 546 | 0.56 | 9.9
Av. 0.55 7.8
HARD MAPLE FACES
BASSWOOD CORE
1/20" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 681 | 0.54 | 7.1
× | 547 | 0.58 | 7.5
Av. 0.56 7.3
HARD MAPLE FACES
YELLOW POPLAR CORE
1/20" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 639 | 0.59 | 7.5
RED GUM FACES
YELLOW POPLAR CORE
1/20" Faces
Various Core Thicknesses
S | Ship. | Sp.Gr | %M
● | 631 | 0.49 | 7.2
× | 552 | 0.50 | 5.7
Av. 0.50 6.5
(A)
(B)
Maximum Unit Load, lb per in of Width
Thickness of Panels in Inches
0 100 200 300 400
0.0 0.1 0.2 0.3 0.4 0.5
Legend: S - Symbol.
Sp.Gr - Specific Gravity Based on Oven Dry Weight and Volume at Test.
% M - Percent Moisture.
A - Load Applied Parallel to Grain of Outer Plies
B - " " Perpendicular to " " " "

FIG. 11.—Effect on Maximum Load per Inch of Width of Increasing Core Thickness of 3-ply Plywood. Test Specimens 12 in. Long. Each Point Represents the Average of Five Tests. Round-Ended Columns.

panel are of the same thickness and species. The marked difference in the bending strength parallel and across the grain should be noted. It will be seen that for both directions, the strength increases approximately as the $\frac{3}{2}$ power of the specific gravity.

Effect on Strength of Plywood of Increasing the Number of Plies.—Increasing the number of plies tends to make the strength properties across the face grain equal to those parallel to the face grain, the former being increased and the latter reduced. The resistance to splitting is materially increased by increasing the number of plies for a given total thickness. (See Table III.)

Effect on the Bending Strength of Increasing the Ratio of Core to Total Thickness of 3-Ply Plywood.—Various combinations of high and medium-strength faces with high or low-strength core woods were tested. The curves of Fig. 10 show that by increasing the core thickness the column-bending modulus of 3-ply plywood parallel to the face grain is reduced and at right angles to this direction it is increased. When all three plies are of the same species, the strength in these two directions are equal for a thickness of core equal to about $\frac{2}{3}$ of the total thickness. When the core is of a low density wood, that is a relatively weak wood, the ratio for equal strength is somewhat greater than $\frac{2}{3}$.

Column-Strength and Stiffness of 3-Ply Plywood having Various Ratios of Core to Total Thickness.—When the ratio of the core to total thickness is increased, as in the curves of Fig. 11, the difference between the column strengths parallel and across the face grain is progressively reduced until a ratio is reached for which the column strengths (also stiffness) in these two directions are equal. The latter condition holds for yellow birch plywood when the core is about 0.8 of the total thickness.

Shear Strength of Various Species of 3-Ply Plywood.—Contrary to most strength properties, the shear strength parallel to the face grain is not greatly different from the shear strength across the face grain, although the latter is in general slightly higher than the former. The results of the shear tests on 29 species are given in Table IV. While the shear values tabulated are not very much higher than the corresponding values for ordinary wood, the method of failure of the plywood is very different from that for ordinary wood. The latter fails suddenly and completely. Plywood, on the other hand, will support a

S	Faces	Core	Sp.Gr.	%M	Position
○	1/2" Birch	1/8" Birch	0.61	6.4	A
●	1/2" Birch	1/8" Birch	0.61	6.5	B

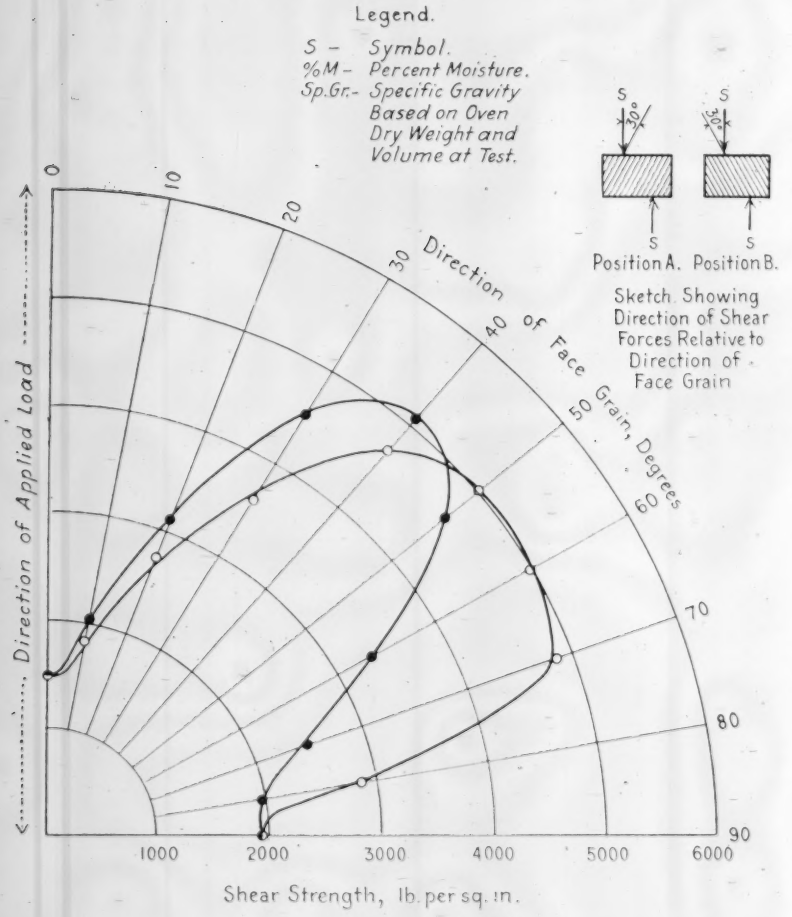


FIG. 12.—Variation of Shear Strength of 3-ply Plywood with Direction of Stress. Length of Shear Specimens 3 in. Distance between Shear Forces ¼ in. Method of Test Shown in Fig 7.

TABLE IV.—SHEAR STRENGTH OF 3-PLY WOOD. VARIABLE SPECIES.

All plies of any one panel were of the same thickness and species.
Grain of successive plies at 90 d.g. All material rotary-cut. Perkins glue, five thicknesses of plywood ranging from $\frac{3}{30}$ to $\frac{3}{12}$ in. were tested.
Each result is the average of about 40 tests.
Size of shear section $\frac{1}{2}$ by 3 in.
Method of test shown in Fig. 13.

Species.	Specific Gravity Based on Oven-dry Weight and Volume at Test.	Moisture Content, per cent.	Shearing Strength, lb. per sq. in.	
			Parallel.[1]	Perpendicular.[1]
Ash, black	0.472	5.7	1 350	1 550
Ash, commercial white	0.556	6.6	1 640	1 770
Basswood	0.408	6.2	1 260	1 370
Beech	0.628	6.4	1 680	1 760
Birch, yellow	0.676	7.6	2 220	2 350
Cedar, Spanish	0.373	12.4	880	960
Cherry (probably black cherry)	0.600	5.6	1 840	2 100
Chestnut (average of tests on $\frac{3}{24}$ and $\frac{3}{20}$-in. thicknesses)	0.409	7.8	1 250	1 420
Cottonwood (probably common)	0.468	7.1	1 350	1 530
Cypress, bald	0.476	9.0	1 200	1 370
Douglas fir (coast type)	0.511	6.8	1 080	1 290
Elm, cork	0.587	6.8	1 580	1 670
Elm, white	0.492	6.4	1 210	1 310
Gum (probably black gum)	0.556	6.9	1 780	1 900
Gum, cotton (average of tests on $\frac{3}{24}$, $\frac{3}{20}$, and $\frac{3}{12}$-in. thicknesses)	0.488	6.8	1 230	1 340
Gum, red	0.578	7.0	1 500	1 820
Hackberry	0.548	7.4	1 250	1 290
Hemlock, western	0.466	8.2	1 410	1 610
Magnolia (probably evergreen)	0.580	7.0	1 710	1 830
Maple, soft (probably silver maple)	0.575	6.4	1 790	1 960
Maple, hard (sugar or black)	0.678	6.2	2 260	2 500
Oak, commercial red	0.625	6.8	1 300	1 510
Oak, commercial white	0.666	8.5	1 340	1 580
Pine, sugar	0.446	6.6	1 310	1 420
Poplar, yellow	0.563	6.4	1 530	1 700
Spruce, Sitka	0.459	7.4	1 280	1 570
Sycamore	0.555	6.7	1 410	1 670
Walnut, black	0.589	6.5	1 560	1 670
Redwood	0.386	8.3	1 080	1 250

[1] Parallel and perpendicular refer to direction of face grain relative to applied load.

very large load in shear after initial failure, and rupture only takes place after considerable work has been done and the plywood is badly distorted.

Relation of Shear Strength to Direction.—The maximum shear strength of 3-ply plywood appears to lie between 40 and 70 degrees to the face grain. The optimum angle will vary with the combination of species and thickness of plies. From the curves shown in Fig. 12, it will be seen that within the range of 40 to

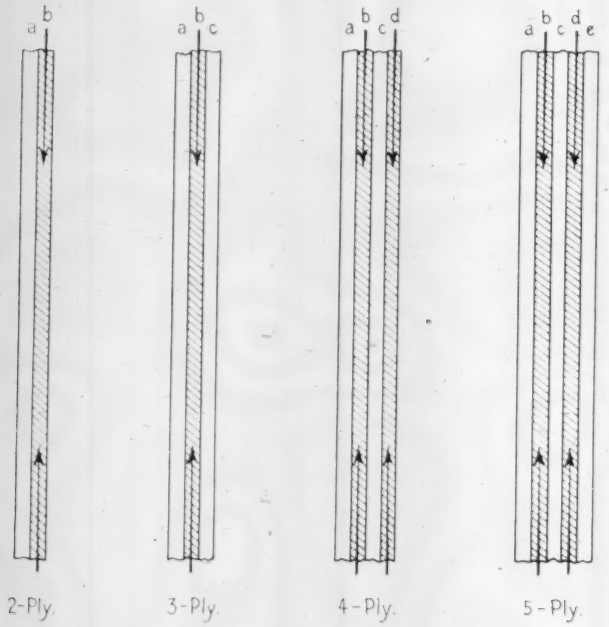


FIG. 13.—Direction of Shrinkage Stresses in Various Plies.

70 degrees the shear strength may be more than twice that parallel to or at right angles to the face grain.

Factors Affecting the Warping of Plywood.—Warping of plywood is due to the unbalanced condition of the stresses resulting from changes in moisture content. A number of plywood panels originally in unstressed condition will be assumed as in Fig. 13. When the moisture content of these panels is reduced, shrinkage in the direction of the arrows follows and stresses are introduced

as if the various plies were so many stretched elastic sheets, successive sheets being stretched in directions at 90 degrees to each other. The 2-ply and the 4-ply panels obviously represent unbalanced conditions; that is in order to obtain balanced stresses an odd number of plies must be used. If now the two faces of a 3-ply or a 5-ply panel consist of veneer of different thickness, unbalancing of the stresses will again follow. Or if the faces are made of veneer of different species or densities,

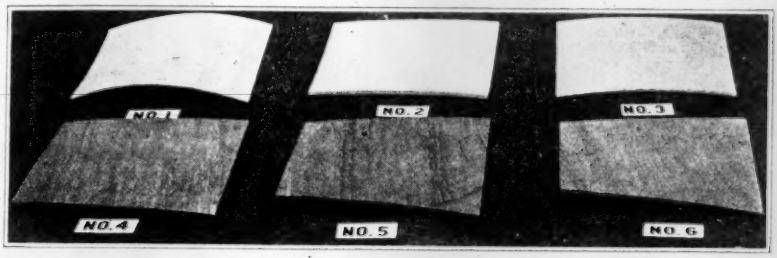


FIG. 14.—Faulty Plywood Construction Causing Warping.

Panel No. 1.—2-ply, $\frac{1}{16}$-in. maple veneer, grain of one-ply at 90 deg. to grain of other.

Panel No. 2.—4-ply, $\frac{1}{16}$-in. maple veneer, grain of successive plies at 90 deg.

Panel No. 3.—3-ply, $\frac{1}{16}$-in. maple veneer, on one face and $\frac{1}{16}$ basswood core, and $\frac{1}{16}$ basswood on other face, grain of successive plies at 90 deg.

Panel No. 4.—3-ply, $\frac{1}{16}$-in. gum veneer, angle between grain of faces 10 deg., between core and faces 85 deg.

Panel No. 5.—3-ply, $\frac{1}{16}$-in. red gum veneer, angle between grain of faces 20 deg., between core and faces 80 deg.

Panel No. 6.—3-ply, $\frac{1}{16}$-in. red gum veneer, angle between grain of faces 30 deg., between core and faces 75 deg.

having different shrinkages or moduli of elasticity across the grain, warping in the form of cupping may again be introduced. If the grain of one face is not parallel to that of the other face, the panel will have a tendency to twist.

Comparatively severe twisting in several panels due to non-parallel construction of the faces is illustrated in Fig. 14. This illustration also shows a number of constructions causing cupping, as, for example, the use of an even number of plies and of face plies of different species.

If panels are properly dried in a restrained or flat position faulty construction if not excessive may not cause serious warping.

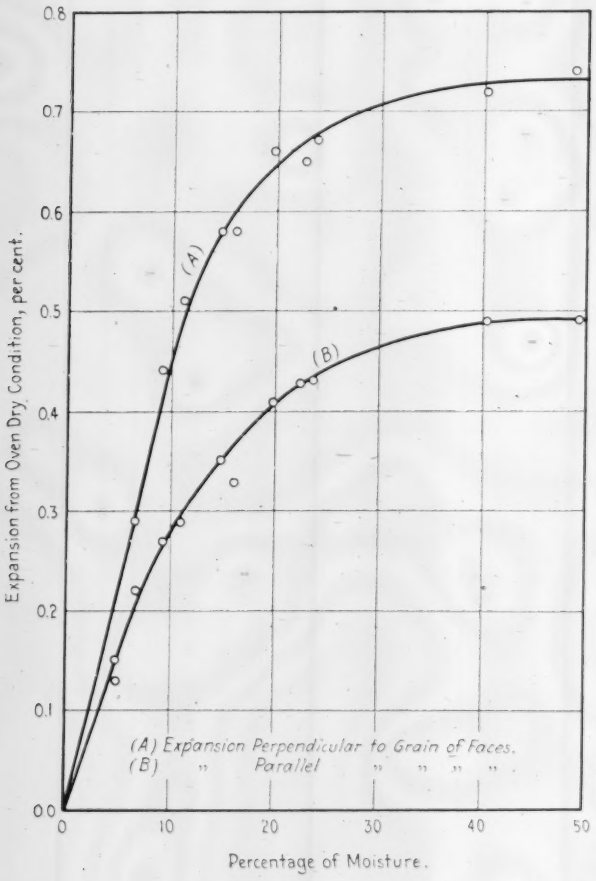


FIG. 15.—Expansion-Moisture Content Curve for Thin 3-ply Birch Plywood.

Shrinkage and Expansion of 3-Ply Plywood with Changing Moisture Content.—The tests made on very thin 3-ply plywood in which all the plies of a given panel were of the same thickness showed that for such constructions the expansion from the oven-dry condition is slightly greater across the grain of the faces than

parallel to the face grain and that the expansion is very small, being comparable with the change in length of wood parallel to the grain. Beyond 25 to 30 per cent of moisture—that is, beyond the fiber-saturation point, very little change in width takes place with increasing moisture. A typical moisture-expansion curve is shown in Fig. 15, expansion and shrinkage apparently following the same curve. Other tests made on thicker plywood showed that when all the plies are of the same thickness, the shrinkage from the soaked to the oven-dry condition is usually slightly less than 0.5 per cent parallel to the face grain and somewhat greater than 0.5 per cent across the face grain.

CONCLUDING REMARKS.

The forces acting on members made of plywood are seldom known with accuracy; so the use of the data given in the various tables and figures included with this paper is limited in exact design. In determining relatively superior constructions, the strength values have, however, a very large application. They assist the designer in selecting species, thicknesses, number of plies, and directions in which grain of the panels should run to obtain the maximum benefit of the plywood.

When using the data the variability of the density and strength of wood should be kept in mind. Individual pieces of a given species may be stronger than the average strength of another species listed as stronger, or they may be weaker than the average strength of a weaker species.

Discussion of the moldability of water-resistant plywood was omitted because the information on this subject has not yet been correlated. The molding of plywood to double curvature from the flat sheet after it has been softened is, however, already developing into an industry of considerable importance.

Acknowledgment.—In conclusion, the author wishes to express his appreciation for the guidance and suggestions offered by various members of the Technical Staff of the Forest Products Laboratory, in particular Messrs. J. A. Newlin and L. J. Markwardt and to Dr. O. H. Basquin of the Haskelite Manufacturing Corporation.

APPENDIX.

Computing the Bending Strength of 3-Ply Plywood Having Cores of Various Thicknesses.

The ratios of core to total thickness for various points on the curves of Fig. 10 were computed for each panel thickness and the corresponding strength parallel to the face grain was found from Curve *A*. The latter strength value was then divided by the strength corresponding to a ratio of core to total thickness of 0.333 and a curve similar to the lower curve of Fig. 16 was obtained. The same procedure was followed for the second series of tests and the two curves averaged with the result shown in the lower curve of Fig. 16.

By dividing the column-bending modulus parallel to the face grain for each ratio of core to total thickness (Curve *A*, Fig. 10), by the column-bending modulus across the face grain (Curve *B*, Fig. 10), for each series of tests and averaging, the upper curve of Fig. 16 was obtained.

We will now suppose that it is desired to know the bending strength of a 3-ply red gum panel in which the core is 0.55 of the total thickness. Table I shows that parallel to the face grain the column-bending modulus is 9970 lb. per sq. in. when all plies are of the same thickness. The strength factor *Q*, Fig. 16, corresponding to a ratio of core to total thickness of 0.55 is seen to be 0.77. Multiplying 9970 lb. per sq. in. by 0.77 gives 7680 lb. per sq. in. as the bending strength parallel to the face grain. Dividing this value by *K* obtained from the upper curve of Fig. 16 corresponding to a ratio of thickness of 0.55 gives the bending strength across the face grain. *K* is seen to be 1.8 so that the bending strength across the face grain is 4250 lb. per sq. in.

While the curves plotted in Fig. 16 were obtained from tests on yellow birch, it seems reasonable to believe that the factors they give are fairly accurate for the other species tested with the possible exception of yucca.

When the core is of a different species from the faces an approximation may be used. In this case, the strength parallel to the grain of the faces may be computed as if all plies were of the face species, and the strength across the grain of the faces computed as before, assuming that the core is of the same species as the faces. The strength value across the face grain obtained

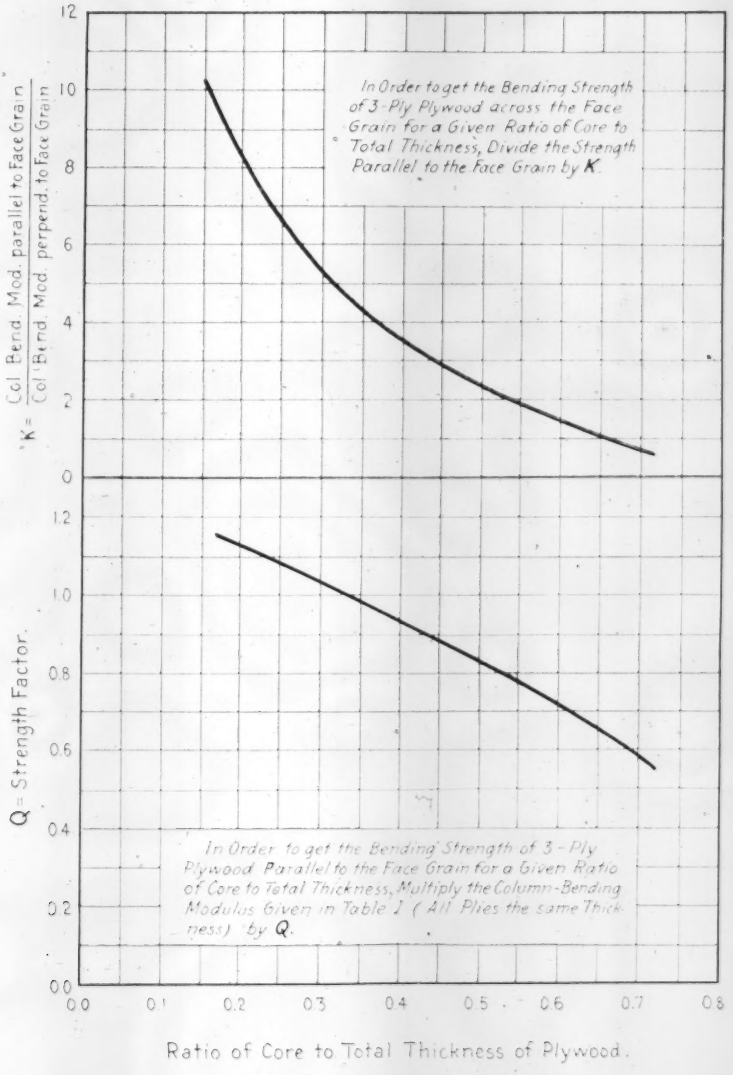

In Order to get the Bending Strength of 3-Ply Plywood across the Face Grain for a Given Ratio of Core to Total Thickness, Divide the Strength Parallel to the Face Grain by K.
K = Col. Bend. Mod. parallel to Face Grain / Col. Bend. Mod. perpend. to Face Grain
In Order to get the Bending Strength of 3-Ply Plywood Parallel to the Face Grain for a Given Ratio of Core to Total Thickness, Multiply the Column-Bending Modulus Given in Table 2 (All Plies the same Thickness) by Q.
Q = Strength Factor.
Ratio of Core to Total Thickness of Plywood.

FIG. 16.—Curves Used in Computing the Bending Strength of 3-ply Plywood having Cores of Various Thicknesses.

in this way will then be multiplied by the ratio of the column-bending modulus of the core species to the column-bending modulus of the face species, thereby yielding an approximate bending strength value across the grain of the faces.

The bending strength values determined as described may then be substituted in the usual design formulas and the thickness of a 3-ply panel of the species and construction chosen necessary to sustain a known bending moment may be computed.

COMPUTING THE STIFFNESS OF 3-PLY PLYWOOD HAVING CORES OF VARIOUS THICKNESSES.

The stiffness of 3-ply panels of various core thicknesses may be computed with a fair degree of accuracy using the moduli of elasticity parallel to the grain given in Table I and substituting in the approximate formula:

$$E = E_1 (1 - k^3 + Rk^3) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where E = the desired modulus of elasticity such as might have been obtained from test data by the use of standard beam formulas or Euler's long column formula, E_1 = modulus of elasticity obtained from Table I, k = the ratio of the core to total thickness, R = ratio of modulus of elasticity across the core grain to modulus parallel to the face grain.

Parallel to the face grain,

$$E = 2110000 \left(1 - 0.6^3 + \frac{0.6^3}{18}\right) = 1{,}680{,}000;$$

across the face grain,

$$E = \frac{1540000}{18} (1 - 0.6^3 + 18 \times 0.6^3) = 400{,}000.$$

In bending across the face grain the core usually contributes much more to the stiffness than do the faces so that the modulus of elasticity of the core wood should be used. In the case considered, the ratio of the modulus of elasticity across the grain of hard maple to the modulus of elasticity parallel to the grain of yellow poplar is probably larger than $\frac{1}{18}$, but a small change in this ratio does not affect the result very much so that the approximate ratio of $\frac{1}{18}$ may be used here as well as in practically all other cases.

[1] Due to Mr. C. B. Norris.

CONSTRUCTION OF STEAM HOSE.

By John M. Bierer.

Steam hose can be constructed with a seamless machine-made tube, or with a tube plied from calendered stock. Furthermore, the hose can have for its fabric element a duck of given weight and number of plies or a combination of plied duck and one or more plies of braid. To determine whether it is more satisfactory both to user and to manufacturer to make a seamless or a plied tube, and to make a simple multiple-ply duck construction or a combination duck and braid construction, three series of tests, carried out individually and independently by the B. F. Goodrich Co., the Goodyear Tire and Rubber Co., and the Boston Woven Hose and Rubber Co., have been made, the results of which are here offered.

The actual steam hose tested by the three investigators was obviously of different material, particularly as to compounds, so it is most reasonable and enlightening to survey the different series separately in order not to make the materials a factor in any comparison of constructions.

The tests by the B. F. Goodrich experimenters endeavored to compare both seamless with plied tubes and simple duck with duck-braid construction. All samples were $1\frac{5}{8}$ in. in inside diameter, with tube $\frac{1}{8}$ in. thick, cover $\frac{1}{32}$ in. thick, duck 20 oz. per sq. yd., and braid 12 2 3 yarn. The hose was tested in a vertical position (so as not to have condensed steam present), under intermittent steam pressures, ten hours under pressure and two hours rest, until failure.

The results of the Goodrich tests are summarized in Table I. Each result represents an average of five individual samples of each construction.

Sample B was of distinctly lighter weight than A or C, so it is not surprising that failure occurred earlier than the A and C samples, which were comparable to each other. C and D were different only in the construction of tube, so that the longer service of C was undoubtedly due to the absence of seams, joints, or plied surfaces, which tend to open up. Similarly, A and C were different in fabric construction, with the same tube, so that the better endurance of C can safely be laid to

the superiority of the simple plied duck to the braid and duck construction.

It takes little studying of these experiments to notice two facts already known to many familiar with steam hose. The steam hose with seamless tube lasted about half again as long as that with a plied tube; and likewise the hose with simple duck of sufficient plies lasted about half again as long as the hose with a combination of duck and braid.

Summarizing the experiments of the Goodyear Tire and Rubber Co., there appears a series of similar results. Table II represents an average of five individual samples of each construction. Comparison is offered in this series also of seamless and plied tubes, of duck and duck-braid constructions, and of expansion and contraction measurements as well. Like the

TABLE I.—RESULTS OBTAINED IN TESTS BY B. F. GOODRICH CO.

	Sample.			
	A	B	C	D
Number of plies of duck	3	4	6	6
Number of plies of braid	2	0	0	0
Tube	Seamless	Seamless	Seamless	Plied
Endurance under 60-lb. pressure, hours	2261	904	3143	2170

Goodrich tests, the hose was tested ten hours under pressure and two hours rest until failure.

Owing to details of manufacture, there is necessarily not found the same percentage ratios of endurance among the various constructions that were found in the Goodrich tests, but inspection of the results will reveal certain facts more important than this detail. The hose with the seamless tube C outlasted that with the plied tube D and the hose with the simple plied duck construction C outlasted that with a combination of duck and braid E. These results, though not so strikingly shown, are in accordance with those obtained in the Goodrich experiments. A further feature should be noted, that though the expansion in lateral dimensions and contraction in length are favorable to the duck-braid construction, the difference is so small between the two styles that any real and

practical superiority for the braided hose would be negligible in practice.

The next experimental data to show divergence among the constructions are those obtained at the Boston Woven Hose and Rubber Co. laboratories. In order to determine the relative value of a hose with simple plied duck and hose with a combination of duck and braid, and to determine the relative value of seamless tubes and plied tubes, the following constructions were given prolonged tests. All hose was of 1-in. inside diameter, $\frac{1}{8}$-in. tubes, 0.050-in. covers, and was tested in 3-ft. lengths. Two series of tests were carried out: the first at 60-lb. steam pressure intermittently 124 hours on and 44 hours rest, the second continuously at 180-lb. pressure, both until failure.

TABLE II.—RESULTS OF EXPERIMENTS OF GOODYEAR TIRE AND RUBBER CO.

	Sample.				
	A	B	C	D	E
Number of plies of duck	2	4	6	6	3
Number of plies of braid	2	0	0	0	2
Tube	Seamless	Seamless	Seamless	Plied	Seamless
Endurance under 60-lb. pressure, hours	1506	1198	1624	1493	1612
Expansion of diameter in 1000 hours, per cent	6.1	12.2	8.2	8.1	7.0
Contraction in length in 1000 hours, per cent	1.6	3.2	3.7	3.6	1.8

Eight individual samples were tested in each series and the results summarized are an average of these:

For a given fabric construction, hose with seamless tubes A lasted about one-fifth again as long and B almost twice as long as those with plied tubes C and D. Furthermore, for the same style of tube, hose with simple plied duck A lasted half again as long and C over twice as long as those with duck and braid construction B and D.

In these tests, owing to particularly careful workmanship on the samples, failure was not due primarily to separation of the seam or joint on the inner surface of the tube. But in the ordinary process of manufacture, without such undue care and special attention, the plied tube is always a danger, and

this splitting and opening up of the tube is practically a fatal objection to the success of any hose by this method. This series is a clear case of superiority of seamless tubes over plied tubes, and of simple plied duck over a combination duck and braid construction.

CONCLUSIONS.

Three different experimental laboratories, working individually and independently, found consistent results in an effort to determine the relative values of seamless and plied tubes, and of simple duck and duck supplemented by braiding. From the data gathered, there are two conclusions concerning these relative values which are obvious and irrefutable:

TABLE III.—RESULTS OBTAINED BY THE BOSTON WOVEN HOSE AND RUBBER CO.

	Sample.			
	A	B	C	D
Number of plies of duck	6	3	6	3
Number of plies of braid	0	2	0	2
Tube	Seamless	Seamless	Plied	Plied
Endurance under 60-lb. intermittent pressure, hours	2607	1770	2143	950
Endurance under 180-lb. constant pressure, hours	67	26	62	17

1. Steam hose made with seamless tubes (in practice by the tube-machine method) is superior in endurance under steam pressure to hose with tube made up of successive plies of a sheeted stock, sometimes known as a calendered tube. The hose with plied tubes was found to fail by the splitting and separation of the seam necessarily formed at the surface of the tube in its construction.

2. Steam hose with its fabric constructed of successive plies of frictioned duck is superior in endurance to, and the practical equal in expansion and contraction of, hose made of a fewer number of plies of duck supplemented by plies of braiding.

The inevitable conclusion must be that it is most advantageous to the user and to the manufacturer alike to construct steam hose with a seamless tube and for its fabric element sufficient number of plies of duck only.

DISCUSSION.

The Chairman.

THE CHAIRMAN (MR. D. E. DOUTY).—I should like to ask the author if, from his experience in the manufacture of steam hose, he feels that it is possible to standardize the duck which is used in the manufacture of steam hose? Does he feel that it is possible to draw a standard specification for hose duck?

Mr. Bierer.

MR. J. M. BIERER.—I think that the different rubber manufacturers are coming to agree more and more upon the style of duck, and though we may not each use exactly the same number of threads in warp and filler, the general construction of the duck can and should be definitely specified for steam hose. The one reason why the manufacturer should be allowed some variation is that he may identify his product if it comes back to him, defective or supposedly defective. The duck allows him to do this nicely. But in general I think the construction of duck can be very closely specified, and there would be better results certainly if there were something more definite than merely allowing the use of all styles of duck and specifying only that it should weigh a certain amount per square yard.

The Chairman.

THE CHAIRMAN.—The tire manufacturers have standardized their duck, and it seemed to me that it might be entirely possible to standardize hose duck. In going into the market for the purchase of duck for the manufacture of steam hose, there might be considerable advantage in being able to buy it on a standard specification, and secure better competition.

A Member.

A MEMBER.—I might say that the Master Car Builders' Association has standardized duck on steam hose and has regular specifications for that purpose. I should also like to ask Mr. Bierer if he has ever had any experience with defective hose breaking at the bend? The company I am connected with uses quite a bit of steam hose, and sometime ago we had occasion to analyze the defective condition. We found a great deal of this removed hose in a very hardened condition, and on examining the inner construction, we found that it was badly cracked at the bend right near the coupling.

Mr. Bierer. MR. BIERER.—Your experience is due to the quality of the rubber compound used in impregnating the fabric rather than to the fabric itself. That is one of the difficulties that manufacturers of steam hose continually face, since rubber usually hardens when it is subjected to steam pressure. In the case you mention, the friction, as we call it, was probably not the best that could be put on the fabric, resulting in too rapid a deterioration. No compound has yet been made that can stand up indefinitely under steam. The life of the hose, however, may be prolonged by increasing the thickness of rubber between the plies, thus making the hose more flexible. Still, I believe that as long as steam hose is used while bent we shall experience this trouble.

IMPROVED ELASTIC LIMIT RECORDER.

By C. H. Marshall.

As the value of the elastic limit has gradually become more universally recognized, numerous devices for making this determination have been used. Most of those, however, either have been too slow for commercial work or have involved complicated attachments to the testing machine. A new method for making elastic limit determinations on a commercial scale has been developed and is being used in the physical testing laboratory of the Westinghouse Electric and Manufacturing Co., at East Pittsburgh, Pa. By this method, tension tests including elastic limit require very little more time than straight tension tests.

This new method is an improvement over the Sumner method, which was described in a paper[1] presented at the annual meeting in 1918. By the Sumner method, the load was recorded on a card attached to the weighing poise and having graduations corresponding to the graduations on the beam of the testing machine, by means of a punching device fixed in front of it. The punching device was stationary and the card moved with the poise. The operator by watching an extensometer and pressing a button at predetermined points of elongation, made a series of punch marks in a straight line across the card, thus recording the loads at which the points of elongation were noticed. From the data thus recorded, a curve was plotted on cross-section paper and the elastic limit was determined on this curve. The plotting of the curve required as much time as pulling the test piece.

With the new method, the same punching device and card holder attached to the weighing poise are used, but a different style card graduated to indicate both elongation and load is used. The punching device, instead of being held stationary, is mounted on an instrument by means of which it is caused to move vertically each time a punch mark is made, thus plotting elongation and load simultaneously in the form of a curve.

[1] J. L. Jones and C. H. Marshall, "Sumner Elastic Limit Recorder," *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, p. 478 (1918).

Description of Curve-Plotting Recorder.—This device, shown in detail in Fig. 1, consists of a guide *A* in which the upright member *B* slides. The cross-bar *C* provides a mounting for the punching device *D*. When installed on a testing machine, this punching device and the magnet *E* are connected in parallel so

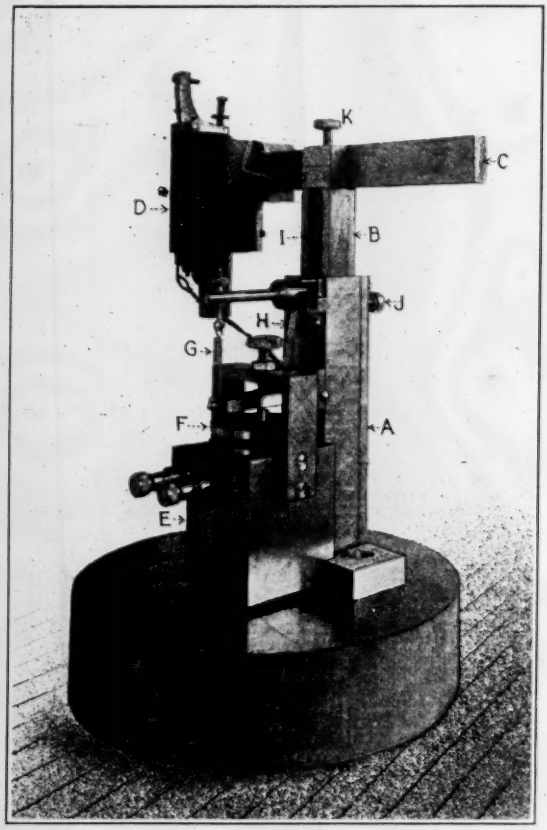


FIG. 1.—Mechanism for Operating Punching Device.

that each time the circuit is closed, the punch operates, and at the same time the armature *F* is attracted, putting the spring *G* under tension and drawing the pawl *H* down to a point where it will engage the next tooth in the rack *I*. A catch (not shown) also engages this rack and while allowing free upward movement,

prevents dropping back. When the circuit is broken, the spring raises the rack one tooth. As the amount of movement is determined by the number of teeth per inch in the rack, the scale on which the elongation is plotted can easily be varied by changing the rack. This change can be made very easily, as the rack is held in position at the bottom by spring tension and at the top by the adjusting screw *K*.

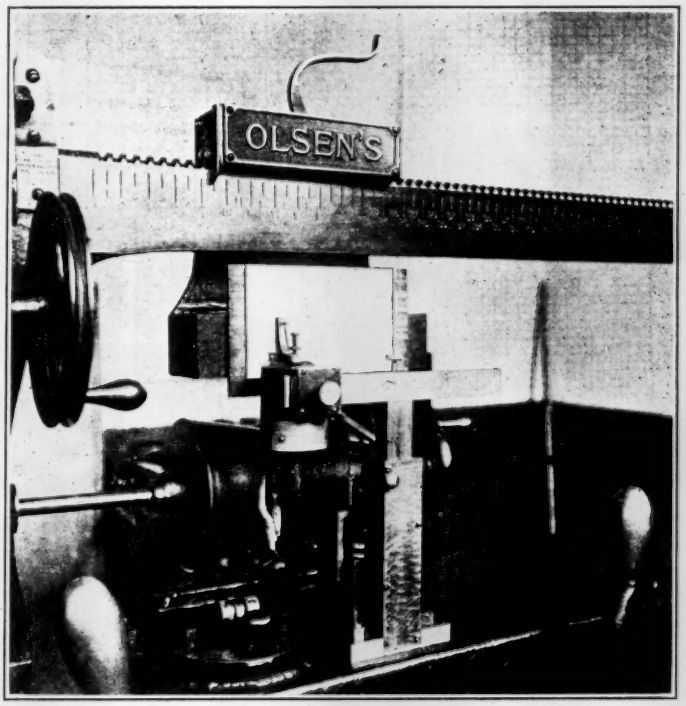


FIG. 2.—Curve-Plotting Attachment in Position.

After the test is completed, the button *J* is pressed. This releases both the catch and the pawl from the rack, allowing it to drop back to the starting position.

Application to Testing Machine.—In Fig. 2, the curve-plotting attachment is shown in position on a 150,000-lb. Olsen testing machine. It is set so that the punching point, when at rest, is about $\frac{1}{8}$ in. from the card on the poise. As there is no

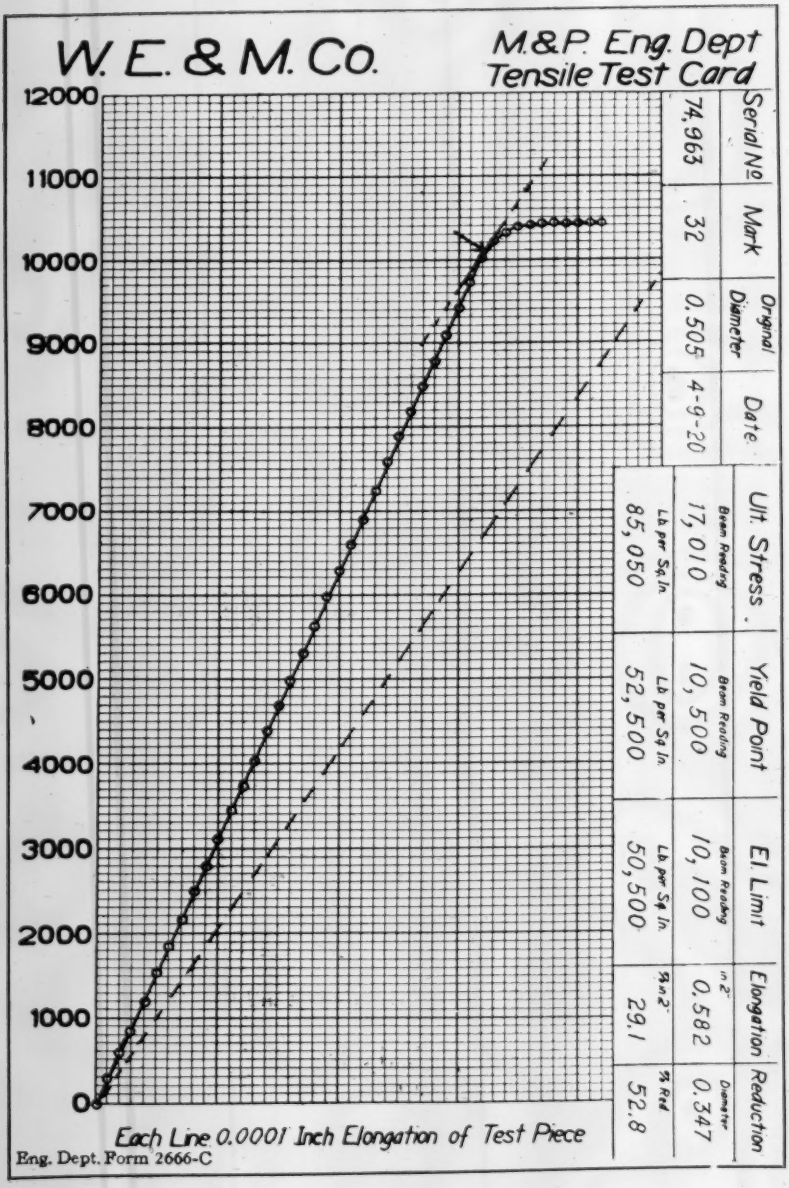


FIG. 3.—Facsimile of Record Card.

mechanical connection with the weighing mechanism, the accuracy obtainable with the recorder is limited only by the testing machine with which it is used. The card shown here is a standard 4 by 6-in. filing size, which we have found suitable for our work. This size of card allows the taking of elastic limits below 12,000 lb. (beam load) without shifting the punching device. When the elastic limit is above this load, it is necessary to stop the machine, move the recorder to the righthand side of the cross-bar and reset so that 12,000 lb. on the beam now indicates zero on the card. In this position, elastic limits up to 24,000 lb., beam load, may be measured. (This would be 120,000 lb. per sq. in. on the standard 0.505-in. diameter test specimen.) By using a larger card, higher elastic limits may be measured without shifting. If this attachment were used with any other size of testing machine, a different size of card would probably be found more suitable.

Operation.—In use, the card (see Fig. 3) is placed in position in the card holder and the testing machine set to indicate zero load. The punching device is then adjusted by sliding along the cross-bar until the punch marks on the card indicate zero load. It is then raised or lowered by means of the adjusting screw (shown at *K* in Fig. 1) so that the first punch mark indicates zero elongation.

The extensometer is then attached to the test specimen, the testing machine is started and the operator, while watching the extensometer, closes the circuit through the recorder by means of a push button, at equal intervals of elongation. After the elastic limit has been passed, the extensometer is removed without stopping the machine and the test completed in the usual manner, the data being recorded in the proper spaces on the card. The card is then removed and a line drawn in by hand connecting the punch marks. The elastic limit or the proportional limit is computed from the curve thus formed. In Fig. 3 the punch marks from which the curve is formed are surrounded by circles. The method of locating the elastic limit on this curve is also shown.

This card may now either be sent out as the report of the test or filed. If desired, two cards may be put in the card holder; the punch marks will penetrate both. One of these may then be filed and the report sent out on the other.

A HIGH-SPEED ALTERNATING TORSION TESTING MACHINE.[1]

By D. J. McAdam, Jr.

An alternating torsion testing machine developed at the U. S. Naval Engineering Experiment Station was described in previous numbers of the Proceedings of the American Society for Testing Materials.[2]

In the machine previously described the torsional moment was measured by means of calibrated springs acting on a lever arm attached to the specimen holder. This method of measurement, however, makes it necessary that the machine be run at comparatively slow speed. If run at high speed, the inertia of the springs and lever arm would be so great as to make accurate stress measurements difficult if not impossible.

Since for practical endurance testing, a slow-speed machine is unsuitable, a new high-speed machine for alternating torsion testing has been developed at the Engineering Experiment Station. In this machine, instead of springs acting on a lever arm, the inertia of a moving mass is used as a means of applying and measuring torsional stress. Inertia has been used in other types of endurance tests, especially in alternate tension and compression tests.

The author has been informed by Professor H. F. Moore that the inertia method has also been used in alternating torsion tests by Stromeyer.

In a high-speed endurance testing machine there are difficulties in the way of definite application of load and accurate measurement of stress. In the machine here described, however, it is believed that these difficulties have been overcome to such an extent that a practicable, high-speed machine has been produced.

[1] This paper is presented by permission of the Secretary of the Navy.

[2] McAdam, "Endurance and Impact Tests of Metals," *Proceedings*, Am. Soc. Test. Mats., Vol. XVI, Part II, p. 292 (1916); also "An Alternating Torsion Testing Machine," *Ibid.*, Vol. XVII, Part II (1917).

The machine illustrated in Fig. 1 was constructed by altering and adapting a machine intended for another purpose. It is intended later to construct a machine especially for high-speed alternating torsion testing.

Fig. 1 is a simplified sketch of the machine at present in use. From the motor M, attached by the coupling L, power is transmitted to a horizontal shaft on which is the fly wheel K. On this shaft is also keyed the wheel A. In a slot in the wheel A, a crank pin C is adjustable to any desired position along the scale B. By means of this crank pin, the connecting rod E, and the vertical arm G, alternating rotation may be given to a shaft passing through the ball bearings H. When the specimen S is inserted in the holders U, the alternating rotation is transmitted to another shaft on which is keyed the fly wheel J.

By the inertia of the fly wheel J, alternating torsional stresses are applied to the specimen. The maximum torsional moment thus produced is proportional to the moment of inerita of the wheel J, to the angular amplitude of oscillation of this wheel, and to the square of the frequency of oscillation. The torsional moment T in absolute units may be calculated from the equation,

$$T = \frac{4\pi^2 I \theta}{t^2} \qquad (1)$$

in which I = the moment of inertia of the wheel J, θ = the angular amplitude of oscillation of the wheel (in radians), and t = the time in seconds required for one revolution of the wheel A.

Since the numerical value of the torsional moment expressed in inch-pounds is $\frac{1}{3\,8\,4}$ of that expressed in the corresponding absolute units, this value must be obtained from Eq. 2.

$$T_1 = \frac{\pi^2 I \theta}{96\, t^2} \qquad (2)$$

In this formula, the moment in inch-pounds is designated by T_1.

Eq. 3 expresses the relation between the torsional moment and the maximum stress in a cylindrical specimen in pounds per square inch.

$$T_1 = \frac{\pi S d^3}{16} \qquad (3)$$

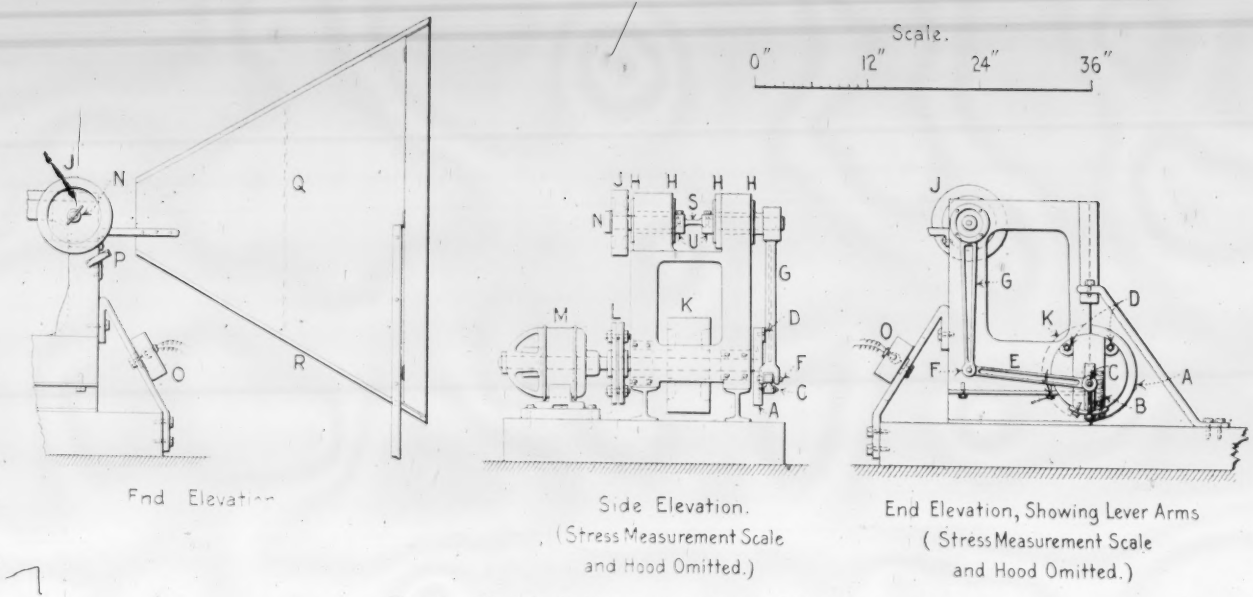


FIG. 1.—Sketch of Alternating Torsion Machine.

In this equation, S = the stress in pounds per square inch and d the diameter of the specimen in inches.

Combining Eqs. 2 and 3,

$$S = \frac{\pi I \theta}{6 l^2 d^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

If the angular amplitude of oscillation of the wheel is expressed in degrees, with the designation ϕ, and the constants are combined, we obtain

$$S = \frac{0.00916 I \phi}{l^2 d^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In the machine now in use, the moment of inertia is 142 lb.-in^2., and the test specimen is 0.5 in. in diameter. For this machine and specimen, therefore, the constants may be combined to give

$$S = 0.002888 \phi \text{ (r.p.m.)}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The accuracy of the stress measurements depends on the accuracy of measurement of the angle of oscillation of the fly wheel J. In the machine illustrated in Fig. 1, provision is made for accurate measurement of this angle by means of the movement of a beam of light reflected from the mirror N to a translucent scale Q. The light tube O, the double convex lens P, and the scale Q, are so placed that an image of a narrow slit in the upper end of the light tube O lies horizontally on the scale Q. Consequently, when the wheel J oscillates through an angle 2ϕ, the reflected beam of light oscillates through an angle 4ϕ thus producing a band of light whose width depends on the distances of O, P, and Q from the mirror N.

In order that the light image may be observed without difficulty, the scale Q is surrounded by the hood R; the image may be observed through a vertical slit in the hood at the edge farthest from the mirror. With this arrangement, the scale may be placed at such a distance from the mirror that the angular measurement is very accurate. In the arrangement at present in use, one-fourth the width of the light band in centimeters is a measure of the value of ϕ in degrees. It is believed that the error in angular measurement, and consequently the error in stress measurement due to angular measurement, is not more than about 1 per cent.

Since the stress is proportional to the square of the speed, it is evident that for accurate testing with this machine the speed must be accurately adjusted and held uniform throughout the test. For accurate speed control, there are several devices on the market that will give suitable accuracy. Consideration is now being given, however, to a device designed to give an accuracy of about one per cent.

Tests thus far with this machine have been made at a speed of 1200 r.p.m. Since at this speed, for an endurance test of 100,000,000 reversals of stress, about two months' continuous running would be required, it is evident that it is desirable to increase the speed to the maximum obtainable value. It is planned, therefore, by means of certain improvements in construction and lubrication, to conduct tests at greatly increased speeds.

Endurance tests with this machine have not been made in sufficient number to justify publication of results at this time.

The writer hereby acknowledges with thanks the assistance of Mr. E. T. Petrik, metallographist, and Mr. L. E. Foster, assistant foreman, of the Naval Engineering Experiment Station, in working out details of this machine.

DISCUSSION.

MR. H. F. MOORE.—Last night in the presidential address emphasis was placed upon the importance of investigating fields not yet covered by standardized specifications. One of those fields today is the study of the shearing strength of metals. The strength tests commonly made are tensile tests; compression tests are rarely made, and shearing tests are even more rare. The Society is fortunate in that at several recent meetings Mr. McAdam has brought to its attention the study of the alternating torsion machine, with the resulting study of fatigue stress in shear. Tonight Mr. McAdam has used, so far as I know, for the first time in America, a machine involving the inertia principle, a type of machine used to some extent in England. So far as I know, Mr. Stromeyer is the only man in England who has used an inertia torsion machine, and his machine lacked many of the refinements of the one described this evening. Mr. Moore.

A very important part of the paper is the note on the necessity of close speed regulation in the inertia type of testing machine. Accuracy of the measurement of stress depends upon the square of the speed. In planning the investigation of fatigue of metals carried on by the National Research Council, the inertia type of machine was considered, but it was found that the frequency of the electric current available, nominally 60 cycles per second, varied from 55 to 65 during the average day. That meant a variation of a little less than ± 10 per cent in the speed and a variation of about ± 20 per cent in stresses. By any of you who may consider using the inertia type of machine for that purpose, this paragraph of Mr. McAdam's paper should be well studied. Be sure that your speed regulation is very close.

AN APPARATUS FOR DELICATE FLEXURE TESTS AND SOME RESULTS OF SUCH TESTS.

By W. J. Francke.

In bending a cantilever specimen, the stress is localized, and even if not localized definitely to an individual crystal there is thought to be a better chance of determining at what stress slip first occurs than in any test where the stress is uniformly distributed over the entire cross-section of the specimen. The stress is localized at the fulcrum of the cantilever, in tension at the top and in compression at the bottom, the neutral axis of the beam forming the long leg of a lever of which the short leg is the distance from the neutral axis to the top or bottom of the beam. Since the measurements of deflection are taken at the end of the long leg of the lever, it follows that if measurements of 0.00001 in. can be taken at that point, it may be possible to note movements, due to slip in a crystal, so small as 0.000001 in. at the short end of the lever.

The screw micrometer was chosen for making the measurements because it was at the time the only means available. The development of the magnetic micrometer which is used in making these tests in combination with an electric switch which multiplies the distance between the contact points, so that a light can be turned on and off for a movement of only 0.00001 in. has made this method of measurement so delicate, convenient and practical in its application, that other methods have not been further experimented with.

The apparatus is shown in Fig. 1. It consists of the base bar *A* to which the lever *B* is attached by means of the lead fulcrum *C* which permits movement of the lever without resorting to any form of mechanical hinge in which there might be lost motion to interfere with the accuracy of adjustment. The short end of the lever carries a micrometer which is insulated from it. The long end is adjustable by means of the screws *D* and *D'*.

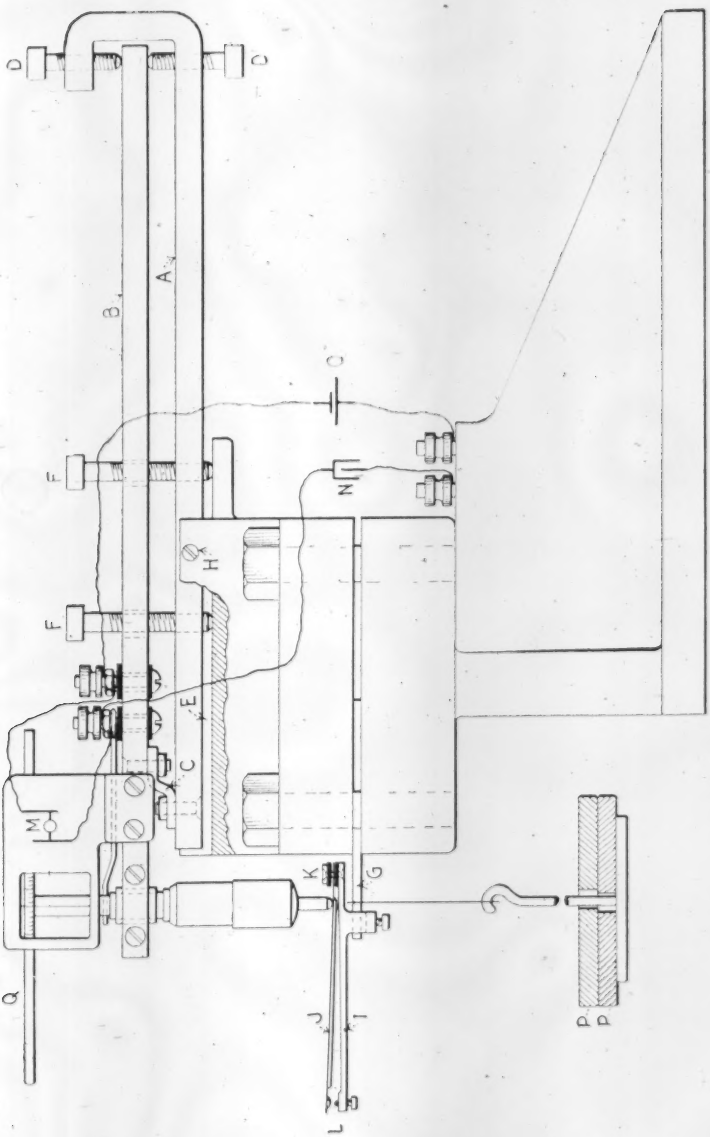


FIG. 1.—Apparatus for Measuring Deflections.

This unit of the apparatus rests in a slot E in the upper vise jaw. It is moveable longitudinally in the slot and may be adjusted up and down by means of the screws F and F'. When the position of this unit of the apparatus is roughly adjusted with relation to the test specimen G, it is clamped rigidly in position by two gib screws one of which is shown at H.

The other unit of the apparatus is clamped to that end of the test specimen which projects from the vise. It consists essentially of an electric contact switch made up of two members I and J insulated from each other at K and having platinum contact points at L. The lower leg I is rigid, the upper leg J is made of flat strip steel about 0.003 in. thick, formed channel-shaped to make it rigid except for a short distance at the fulcrum end.

Readings are taken by means of an electric light M with a condenser N connected in the circuit to reduce arcing at the contact points L. The battery is shown at O and the application of the weight increments to deflect the specimen, at P. The micrometer is equipped with a disk Q graduated on its circumference to 0.0001 in. Readings to 0.00001 in. may be made by means of a vernier or by interpolation.

The micrometer is a permanent magnet. When it is screwed downward to take a reading, it picks up the upper leg J of the contact switch at a point near the fulcrum, thus multiplying the arcing space between the contact points at the other end of the switch. This multiplication may be carried to an extent where the light goes on and off for a movement of 0.00001 in. at the point where readings are taken. Such pressure as is produced in making the electric contact is made uniform by lowering the magnetically-suspended switch to make the contact instead of pushing it down. When making a test, the specimen is clamped in the vise and the electric switch is clamped to the specimen; then the micrometer is adjusted to zero by means of the fine adjusting screws D and D', allowing time for any inequalities in temperature of the specimen and vise to equalize. The test is not begun until the zero reading becomes permanent.

The weights causing the deflections are applied in uniform increments. A reading for deflection is taken for each weight

increment and recorded, then all weight is removed and a reading recorded for permanent set. This procedure is repeated to the conclusion of the test.

Specimens should be prepared by grinding, so that a practically flat surface is available for clamping in the vise.

The specimens used in the tests described in this paper were filed up by hand. As they are small, usually less than $\frac{1}{8}$ in. square, this is easily done; but the surface clamped in the vise is apt to be slightly rounded so that the danger of indentations by the vise jaw is increased.

Errors are confined to those in the micrometer itself, to temperature errors and to possible spring in the lever due to forcible and improper adjustment. Micrometer errors are reduced by having the micrometer vertical and weighted. When a specimen is clamped in the vise and the micrometer adjusted to zero, the adjustment may not in all cases remain immediately permanent; some minutes may elapse before it becomes permanent; this temporary error may be due to difference in temperature between the specimen and the vise or to slowness of the lead hinge in adapting itself to a change of shape.

Another possible source of error is indentation on the lower side of the specimen by the edge of the vise jaw, which would be measured as deflection and therefore cloud the accuracy of results. This matter was called to my attention by Prof. H. F. Moore.

Indentation by the edge of the vise jaw leaves no mark which may be seen with the aid of an ordinary magnifying glass on hard specimens, nor on soft specimens at low stress; on soft specimens at high stress, however, such indentation may be seen without the aid of a magnifying glass in cases where the surface of the specimen is not flat, and indentation shows up on the high spots. It is probable that no indentation takes place in hard specimens and in soft specimens only after permanent bending takes place, and that indentation is negligible in specimens of small section because the total weight employed is too light to cause indentation.

Errors in stress determinations due to using the common fermula for flexure beyond the yield point have been neglected.

Differences due to differences in section of the specimen have not been investigated although circular sections, rectangular costions and rectangular sections reduced in area at the fulcrum have been tested.

NOMENCLATURE.

It is characteristic of tests made with this apparatus that for nearly all material so far experimented with, six points representing physical changes in the material are developed. The names applied to these points are tentative. In all diagrams they are designated as *F.*, *F. R.*, *Y. Pt.*, *Y. R.*, *P. L.* and *R.* meaning respectively "Fatigue," "Fatigue Range," "Yield Point," "Yield Range," "Plastic Limit," and "Rupture." These terms are defined as follows:

Fatigue is the point where crystals begin to slip or the stress at which failure in the Ferrite constituent is presumed to take place.

Fatigue Range is presumed to indicate the range in which slip in Ferrite continues or the point where failure in Pearlite begins.

Yield Point probably does not record a point where movement first takes place in any crystalin constituent of the material. It is possible that slip in Ferrite crystals has been sporatic up to *F. R.*, taking place in crystals least favorably situated to withstand stress and allowing time for amorphous to harden before other crystals fail. At *F. R.* movement begins to take place in the Pearlite constituent, possibly through slip in Pearlitic Ferrite, resulting in increasing deformation of the test specimen as a whole which in turn causes increasingly greater stress to be thrown on the Ferrite crystals which, with diminishing support of the stronger Pearlite, slip in increasing number, slowly at first but in some material soon reaching a point where the slip in many crystals becomes cumulative, time is not allowed for the hardening of the amorphous and a "flow" takes place on many slip planes simultaneously causing the phenomena of the yield point manifested by the drop-of-beam in a tensile testing machine, but not recording a point where failure has first taken place in any crystalin constituent of the material, but recording rather a movement of the amorphous constituent in the slip planes.

Yield Range records the range of this flow, and marks the point where it ceases due to the hardening of amorphous metal in the slip planes permitted by slowing up of the flow due to the gradually decreasing number of large crystals, which have now been divided and subdivided by slip, and the exhaustion of the

supply of crystals unfavorably situated to resist stress. The material is now presumed to have undergone a complete physical change which began at *F*. with slip in Ferrite Crystals. We are now dealing in a sense with a new material, that is strain hardened steel in which the intergranular amorphous cement has not yet fully hardened and still has some mobility which, however, is probably permitted by a slow movement of the not fully hardened amorphous metal between the subdivided crystals as distinct from the earlier "flow" due to slip in crystals.

Plastic Limit marks the end of this movement and is comparable with the maximum strength of the material where necking begins in a tensile test.

Rupture is presumed to be comparable with ultimate strength.

The six points noted are characteristic of hypo-eutectoid steel. It has not been shown that all of them would appear in pure iron where there is only one crystalin constituent, or in a eutectoid steel composed of all Pearlite; in these cases only one point may show up below the yield point.

There is also some indication that the Yield Point may be absent in tests of some severely strained material in which the crystals have been greatly subdivided by slip and in which the "flow" which causes yielding has taken place before the test is made, especially if the specimen has been subjected to low heat treatment which seems to check the tendency to yield in strained material.

The Yield Point may also be of indefinite or doubtful appearance in alloy steels if the alloy prevents a "flow" from taking place due to chemical combination of the alloy in Cementite or its solution in Ferrite. In these cases the *Y. R.* point is usually more prominent than the yield point.

The data in Table I is for a specimen of machinery steel, the section and length being such that a 1-lb. weight increment produces a stress of 2500 lb. per sq. in. in extreme fiber. In column No. 1 is recorded the deflection produced by each weight increment and in column No. 2 the permanent set when all weight is removed.

Columns Nos. 1 and 2 are plotted in Fig. 2 beginning at the lower left-hand corner. The "deflection line" shows the deflec-

tion caused by each weight increment and the "set line" the permanent set remaining when all weight is removed. The delicate accuracy of the apparatus is shown by the uniformity of the curve, which is constructed by connecting the plotted points by straight lines.

TABLE I.

	Deflection.	Set.	Deflection Difference.	Deflection Difference Minus Basic Deflection = Increase in Deflection per Weight Increment.	Total Increase in Deflection over the Basic Deflection = Distortion.	Distortion Deflection.	Set Deflection.
	1	2	3	4	5	6	7
	0.00058	0.00003	0.00058	0.000073			
	114	10	56	53			
	173	18	59	84		0.00053	
	232	29	59	83		0.00357	
	297	39	65	143			
F.	0.00357	0.00053	0.00060	0.000094	0.000530	0.148	0.148
	429	73	72	213		0.00114	
	499	92	70	193		0.00570	
F.R.	0.00570	0.00142	0.00071	0.000204	0.001140	0.200	0.195
	647	138	77	263			
	729	168	82	313		0.003096	
	813	200	84	334		0.010190	
	917	241	104	533			
Y. Pt.	0.01019	0.00290	0.00102	0.000513	0.003096	0.303	0.284
	1159	362	140	894			
	1302	439	143	923			
	1505	567	203	1523		0.035583	
	1738	722	233	1824		0.046400	
	2120	1029	385	3343			
	2770	1608	650	5993			
	3680	2465	910	8594			
Y. R.	0.04670	0.03353	0.00990	0.009393	0.035583	0.762	0.717
	6050	4691	1380	13293		0.074763	
	7460	5997	1410	13594		0.087400	
P. L.	0.08740	0.07285	0.01280	0.012293	0.074763	0.855	0.833
	10600	9060	1860	18093		0.128843	
	12700	11098	2100	20494		0.142000	
R.	0.14300	0.12619	0.01600	0.015493	0.128843	0.900	0.882
	0.16800	0.15043	0.02500	0.024493			

$$\text{Basic Deflection} = \frac{\text{Deflection} - \text{Set}}{\text{No. of Weight Increments}} = \frac{0.00357 - 0.00053}{6} = 0.0005066+$$

This curve has little practical value. Close examination, however, will show that it is not a straight line even at the beginning; it curves slightly up to *F.*, is almost straight from *F.* to *F. R.*, curves again from *F. R.* to *Y. Pt.* and curves markedly

beyond *Y. Pt.* This slight curvature even at low stress is characteristic of practically all material experimented with and it was a persistent search for the reason of this curvature that resulted in the isolation of the point *F*. by the following method of plotting.

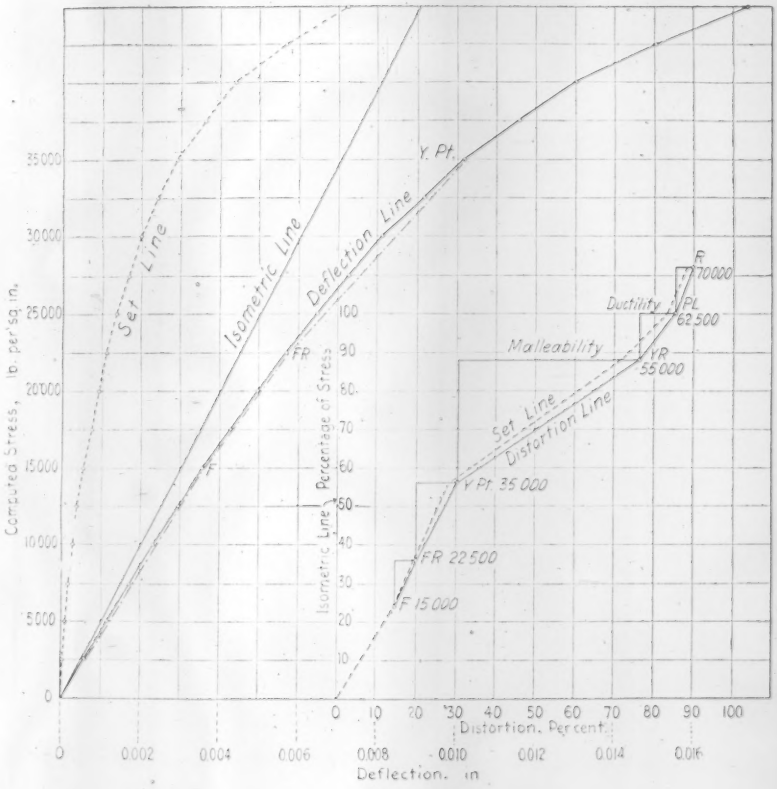


FIG. 2.—Percentage Diagram.

In column No. 3 of Table I are entered the differences between each deflection reading and the next following one, showing therefore the deflection caused by each weight increment. It is characteristic of this method of testing to have this column of "differences" show groups of readings, each succeed-

FIG. 3.—A Comparison of a Plot of Column No. 4 in Table I with a Stress-Deformation Diagram.

ing group indicating where a change has taken place in the material under test.

The end of the first group, point *F.*, is assumed to be the fatigue point for the reason that as far as records of endurance test have been available for comparison, the stress at this point coincides approximately with the stress at which slip first takes place.

It will be noted that up to this point *F.*, quite a pronounced and fairly regularly increasing permanent set is recorded. This feature of an increasing permanent set taking place at stresses lower than the stress at which slip in crystals may be expected is also characteristic of all material experimented with although the value of it compared with the deflection varies greatly in different materials. It is assumed that this permanent set below *F.* is caused by some movement other than that due to slip and it is ascribed, in the absence of definite knowledge, to movement in amorphous metal.

With these assumptions, column No. 4 is arrived at by ascribing all movement below *F.* to distortion in amorphous metal and all movement above *F.* to distortion in both amorphous metal and crystalin metal, the word distortion being used to express movement in the constituents of a material as distinct from deformation which is used to express movement in the test specimen as a whole.

If we now deduct the deflection caused by distortion in amorphous metal below *F.* from the total deflection at *F.*, where no crystalin distortion has yet taken place, we may use the remainder, that is the deflection at *F.* minus the set at *F.*, where crystalin distortion is zero, as a basic deflection from which to measure the distortion in constituents above *F.* In this case this basic deflection is: deflection at *F.*, 0.00357, minus set at *F.*, 0.00053, = 0.00304 and dividing this by the number of weight increments at *F.*, 6, we have the average basic deflection per weight increment, 0.000506+, being the deflection caused by one weight without set and without crystalin distortion, representing therefore theoretically, but only for the purpose of plotting, the deflection of perfectly elastic material at this point.

This basic deflection plotted against uniform weight increments is shown on the diagram as the isometric line.

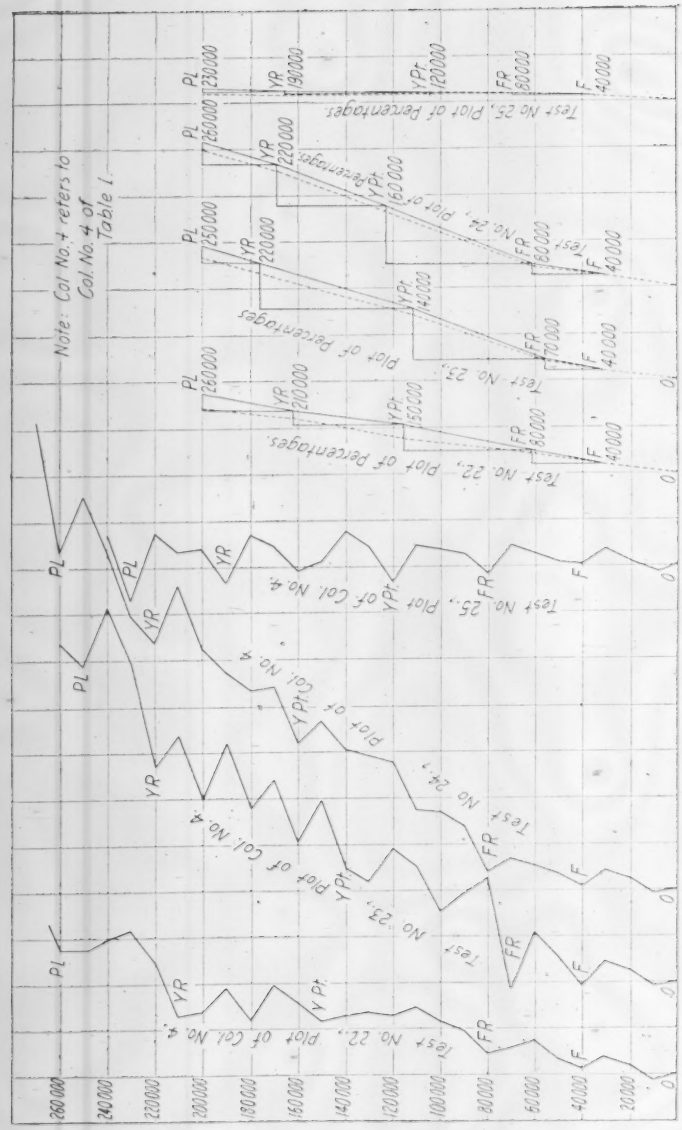

Note: Col No. 4 refers to Col No. 4 of Table 1.
Test No. 25., Plot of Percentages.
Test No. 24., Plot of Percentages.
Test No. 23., Plot of Percentages.
Test No. 22., Plot of Percentages.
Test No. 25., Plot of Col. No. 4.
Test No. 24., Plot of Col. No. 4.
Test No. 23., Plot of Col. No. 4.
Test No. 22., Plot of Col. No. 4.
PL
YR
YPt.
FR
F
As Drawn
As Drawn Strained
As Drawn Strained Tested after 3 Hours
As Drawn Strained Tested after 8 Days
As Drawn Strained Bued.
— Patented Wire Tested in Circular Section —

FIG. 4.

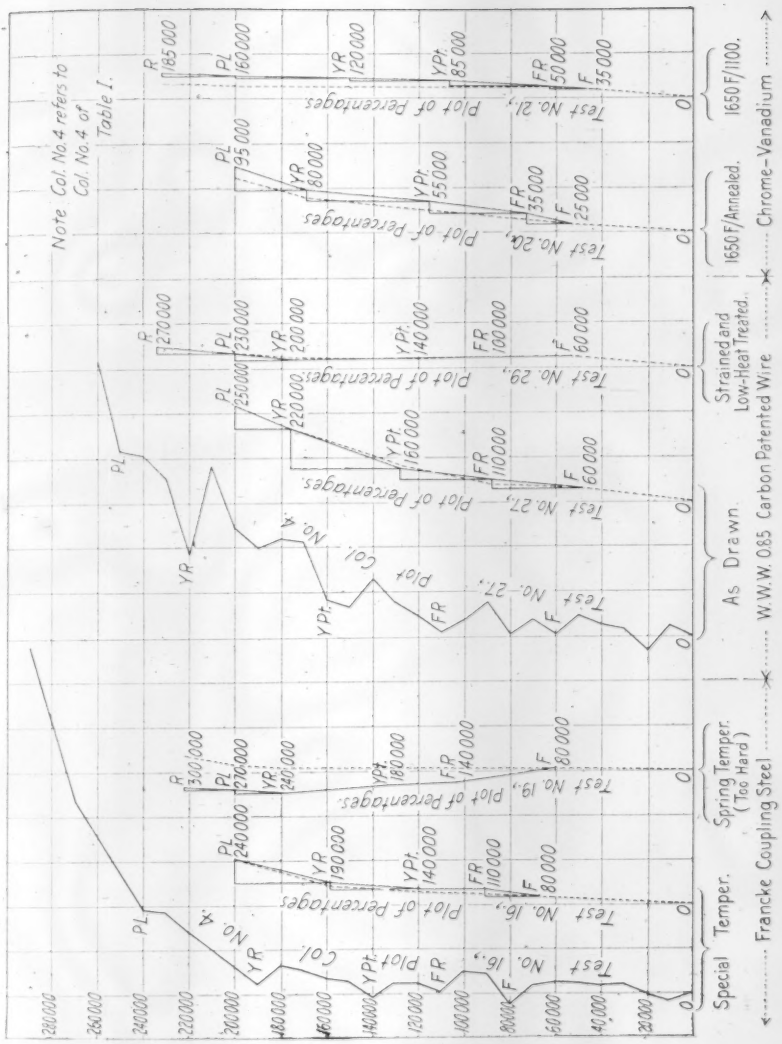

Note Col. No. 4 refers to Col. No. 4 of Table I.
Test No. 21, Plot of Percentages
Test No. 20, Plot of Percentages
Test No. 29, Plot of Percentages
Test No. 27, Plot of Percentages
Test No. 19, Plot of Percentages
Test No. 16, Plot of Percentages
Col. No. 4 Plot
Special Temper.
Spring Temper. (Too Hard)
As Drawn
Strained and Low-Heat Treated.
1650 F/Annealed.
1650 F/1100.
Francke Coupling Steel
W.W. 085 Carbon Patented Wire
Chrome-Vanadium

FIG. 5.

Column No. 4 shows the remainder, after deducting this basic deflection per weight increment from the "differences" in column No. 3 and therefore the increase in deflection per weight increment, or decrease, in case the basic deflection is greater than the "difference."

Column No. 4 is plotted in Fig. 3 in comparison with a stress-deformation diagram which is drawn to no scale and inserted merely to show at what part of the stress-deformation diagram the points *F.*, *F. R.*, *Y. Pt.*, *Y. R.*, *P. L.* and *R.* appear.

It will be noted that column No. 4 shows the 6 "groups" more markedly than column No. 3 and that the plotting of column No. 4 brings them out quiet clearly. It will be interesting now to look back at the deflection plottings from column No. 1, Fig. 2, and note that the groups are also indicated there, although they are not so clearly defined. The groups often appear so clearly on the data sheets that the plotting of column No. 4 is not necessary in order to locate them.

PERCENTAGE DIAGRAM.

Diagrams of practical value for comparing different materials cannot be plotted from column No. 4 on account of the long horizontal leg above *Y. Pt.* in ductile material.

In order to get a diagram by means of which material differing greatly in physical characteristics may be more readily compared with each other, columns Nos. 4 and 2 are plotted on a percentage basis, plotting distortion in percentage of deflection, and set in percentage of deflection. This plotting also makes the distortion graphically comparable with the set. The stress at *P. L.* is taken at 100 per cent. The line of origin for this diagram is the isometric line which is a straight line, being the basic deflection before referred to plotted against uniform weight increments.

Such a diagram is shown in Fig. 2. The distortion line is plotted from column No. 6 showing the total distortion which has taken place up to each point in percentage of deflection at that point. The set line is plotted in the same manner from column No. 7. Column No. 5 shows the total distortion up to each point.

Below *F.* this diagram shows the percentage of distortion which has taken place before crystalin distortion began, presumably amorphous distortion.

The little triangles on the distortion line show what has taken place between group points and may reasonably be expected to indicate the quality of that constituent of the material which failed during this period. The horizontal leg shows the distortion which has taken place and the vertical leg the stress that caused it.

The triangle above *Y. Pt.* probably registers the "flow" period of material during which there is great mobility of amorphous as distinct from the plastic period between *Y. R.* and *P. L.* where the amorphous metal has become set but is not fully hardened. The flow period representing maleability and the plastic period ductility.

In a similar manner the triangle between *F.* and *F. R.* may indicate the fatigue quality of a material, for a high fatigue point may not necessarily mean high fatigue quality. A material with a high fatigue point may fail rapidly after slip once begins and a material with a lower fatigue point may conceivably stand more reversals of stress if the injury caused by slip is less due to a difference in the nature of the material. Materials from which a large number of reversals of stress may be expected usually show a small triangle above *F.*

Tests on 0.85 carbon patented wire show that aging strained sorbitic steel for 8 days has little effect except to raise the yield point and maximum while the effect of low heat treatment is very marked as shown in tests Nos. 24 and 25.

A specimen of patented wire strained and low heat-treated for these tests by Mr. E. H. Webb, to whom I am indebted for assistance in preparing specimens, is shown in Test No. 29. In this specimen there is no distortion at all up to *Y. R.*, the diagram being practically a straight vertical line from *F.* up, the set line coinciding with the distortion line.

THE TIME ELEMENT.

With annealed material, tests may be made up to *F.* as rapidly as readings can be taken and recorded and usually up to *F. R.*, the light promptly becomes steady showing no farther deflection. From the yield point up more time is required.

With heat-treated material, usually the deflection caused by

each weight increment comes promptly to a definite rest where readings may be taken.

Strained material generally is slow, and waiting for the specimen to come to complete rest would take a considerable time. In the early part of the test, however, there is little difficulty.

Strained sorbite is very slow, some tests having taken 5 hours and then the readings were taken before the specimens came to rest. Such material would probably yield very slowly, perhaps for days, for each weight increment. This slow yielding is completely arrested by heating the specimen to about 500° F. for a minute and the diagram plotted from the low heat-treated specimen takes the shape characteristic of the diagram plotted from a quenched-and-tempered spring specimen.

DISCUSSION.

Mr. H. F. Moore.—It seems to me that Mr. Francke has presented a very suggestive paper, and three points in his paper appealed to me as especially worthy of comment. The first was the attempted use of the small flexure specimen for testing material. By tradition and convenience it has become customary to use the tension test as the standard test. Flexure tests present the advantage of light machines and small loads, but have never been used to any great extent. Mr. Francke seems to have a most interesting method of using a small flexure specimen. The second point I want to comment on is the delicacy of the micrometer measuring device. It has added another figure beyond the decimal point to the sensitiveness of measurements with the micrometer as they are ordinarily made. The third significant point is that Mr. Francke has called attention to inelastic phenomena, not fully understood, which occur below what is ordinarily called the elastic limit. It may be worth while to think of the basis of Hooke's law, which is fundamental to the entire science of mechanics of materials. If that law is examined it is found to rest entirely on experimental evidence, and its application involves the assumption that our materials are perfectly homogeneous and that the stress is applied to them in a completely known way. Or, put in another way, we imagine our materials to be made up of minute cubes of perfectly homogeneous material, equally strong in all directions, and glued together with glue just as strong as the material. Actual material is not like this, and Mr. Francke suggests that it may be possible to measure at what point different constituents of materials fail. His point seems to be worthy of careful consideration, though much more investigation will be necessary before such tests are quantitatively useful. Mr. Moore.

Mr. A. H. Beyer.—An inspection of the test data given in Table I of Mr. Francke's paper shows for all loads well within the elastic limit of the material an unusually high ratio of permanent set to total deflection, this ratio ranging from 5.2 per cent Mr. Beyer.

Mr. Beyer. at a fiber stress of 2500 lb. per sq. in. to 24.6 per cent at 30,000 lb. per sq. in. The actual relation for the intermediate loads is as follows:

FIBER STRESS, LB. PER SQ. IN.	TOTAL DEFLECTION, IN.	PERMANENT SET, IN.	RATIO OF SET TO DEFLECTION.
2 500	0.00058	0.00003	0.052
5 000	114	10	0.088
7 500	173	18	0.104
10 000	232	29	0.125
12 500	297	39	0.131
15 000	357	53	0.149
17 500	429	73	0.170
20 000	499	92	0.188
22 500	570	112	0.197
25 000	647	138	0.213
27 500	729	168	0.230
30 000	0.00813	0.00200	0.246

These appreciable permanent sets indicate internal structural readjustments in this material at stresses well within the elastic limit.

One fact not brought out in Mr. Francke's paper is the effect upon the stress, strain, and set relation of repeated loading made well within the elastic limit. If under repetitions of load the permanent sets are progressive, it would be indicative of a gradual deterioration of the material. If, on the other hand, these permanent sets entirely disappear on further loading, the permanent sets recorded on the first application of the load would only indicate internal structural readjustment in the material to adapt itself to this particular kind of stress. Such a condition might be brought about by a readjustment in the internal strains which are set up in such materials during their process of manufacture. The effect of such initial strains upon the elastic properties of a material would, under the first application of load, be much more pronounced when the specimen is tested in flexure than when tested under axial loading. These structural readjustments, unless progressive, cannot be considered destructive. The strain, stress and set relations secured from a test on virgin material cannot be a true index of these relations under working conditions, for if they were, no spring balance could be kept in perfect adjustment.

I should like to ask Mr. Francke if, in his extensive investigations, he has determined the effect of repeated application of loads made well within the elastic limit of the material. Mr. Beyer.

MR. W. J. FRANCKE (*Author's Closure, by letter*).—At the time Mr. Beyer raised the question of the effect of repeated applications of loads made well within the elastic limit no tests to determine this point had been made. Since then I have made some tests which show that when steel is tested up to the *F* point and then tested a second time in the same direction, the permanent sets disappear and remain absent in a third test in the same direction, indicating that under repeated loading up to the *F* point, in the same direction, the sets are not progressive. Mr. Francke.

If, however, the steel is tested up to the *F* point in one direction and then tested again but in the opposite direction, the sets appear in both tests and they continue to appear if the specimen is tested repeatedly first in one direction and then in the opposite direction. The value of the set obtained when the specimen was reversed the first time is approximately double that obtained in the first test and then remains greater than for the first test for all subsequent reversals, but fairly uniform, indicating that under this reversal of stress condition, also, the sets are not progressive.

There seems to be a "back-and-forth" movement that suggests a certain looseness of structure, as if it were permitted by some plasticity of the amorphous envelopes surrounding the crystals. That this movement was quite large in the machine steel specimen is shown by the table computed by Mr. Beyer from Table I of my paper and shown in that table in column No. 7 for the various "points." This back-and-forth movement varies greatly in steels of different quality and under various heat treatment. Thus, in the accompanying table are given deflections, set and ratio of set to deflection for a spring quenched and drawn at a rather low temperature, making a live, active spring, somewhat hard and probably troostitic in structure. The ratio of set to deflection at the *F. R.* point is only 0.6 per cent as against 19.5 per cent for the machine steel specimen. Another spring drawn at a little higher temperature and probably approaching a sorbitic structure, showed a ratio at the *F. R.* point of 2.2 per cent.

Mr. Francke. The effect of this back-and-forth movement on a spring balance made from a spring such as that in the accompanying table would be that with the spring used in tension the error of 0.6 per cent due to the back-and-forth movement would be eliminated on the first application of load; the spring balance if

	Fiber Stress, lb. per sq. in.	Total Deflection, in.	Permanent Set, in.	Ratio of Set to Deflection.
	10 000	0.00388	0.00002	0.0051
	20 000	792	8	100
	30 000	1195	12	100
	40 000	1599	17	106
	50 000	1997	20	100
	60 000	2403	22	91
	70 000	2782	23	82
F.	80 000	0.03151	0.00027	0.0085
	90 000	3562	29	81
	100 000	3919	30	76
	110 000	4302	30	69
	120 000	4652	31	66
	130 000	5029	32	63
P. R.	140 000	0.05308	0.00032	0.0060
	150 000	5718	34	59
	160 000	6082	37	60
	170 000	6481	38	58
Y. Pt.	180 000	0.06804	0.00039	0.0057
	190 000	7139	42	59
	200 000	7484	43	57
	210 000	7869	50	63
	220 000	8122	56	69
	230 000	8521	62	72
Y. R.	240 000	0.08852	0.00077	0.0087
	250 000	9241	90	97
	260 000	9659	119	123
P. L.	270 000	10027	0.00156	0.0156
	280 000	10485	321	306
	290 000	10865	354	326
R.	300 000	0.11199	0.00398	0.0355
	310 000	0.11720	0.00489	0.0417

then calibrated would remain in adjustment as long as the spring is used in tension. If, however, this spring were used in compression, the balance made from it would probably have to be recalibrated for an initial error of 1.2 per cent. It is of course possible that the back-and-forth movement may be absent or negligible in a perfectly tempered spring.

Mr. Francke.

The value of the back-and-forth movement is shown in percentage of deflection at the point *F* in all percentage diagrams. It is subject to any error in making the initial adjustment of the testing apparatus to zero.

The statement in the summary of my paper, that it may be possible "to determine the quality of the constituents of material", to which Mr. Moore probably refers as a possibility of measuring "at what point different constituents of materials fail," has some further confirmation in a test of an aluminum alloy, the microphotograph of which clearly showed two constituents: aluminum crystals and what appeared to be an aluminum-copper eutectic. Tension tests developed only two points, a yield point and the maximum. Flexure tests showed that the aluminum constituent failed at a stress below that of the tensile yield point, and that the eutectic failed at a higher stress than the tensile yield point. The strength of each constituent was determined by the test.

Referring to Mr. Moore's suggestion that the basis of Hooke's law involves the assumption that our materials are perfectly homogeneous, it is interesting to note that column No. 4 of Table I, which gives the increase in deflection per weight increment, always shows that this increase is not uniform; as, indeed, it cannot well be in material made up of crystals of varying strength and size, having cleavage planes at various angles to the direction of stress and surrounded by a medium assumed to be amorphous metal which, as indicated by the back-and-forth movement previously discussed, may not be stable.

A NEW METHOD FOR CALIBRATING BRINELL HARDNESS TESTING MACHINES.

By J. L. Jones and C. H. Marshall.

While making a series of Brinell tests which required a greater degree of accuracy than usual, it was found in the physical testing laboratory of the Westinghouse Electric and Manufacturing Co., at East Pittsburgh, Pa., that results obtained by two different machines did not agree. Although the loads recorded by the gages were identical, the diameters of the impressions were not the same. Naturally the gages were thought to be incorrect; but even after the gages had been carefully standardized, the different machines gave results which did not agree. The need of a convenient means of checking these machines directly was felt and the simple lever balance was built and found to answer the purpose very well.

Description.—This balance consists of a single beam and a support. They are made of forged steel, machined for lightness and finish, with hardened steel knife edges and bearings. The knife edges are so placed that a multiplying ratio of practically 25 to 1 is obtained. This ratio, as checked by placing the beam in a 5000-lb. Riehle testing machine, was found to be 25.02 to 1. The beam alone was found to exert an upward pressure of 322.3 kg. A hanger and several lead disks of convenient size were made and carefully weighed. By applying these weights, it is possible to obtain various pressures up to a maximum of 3000 kg.

In calibrating a machine, the adjusting screw is removed and replaced by the support, which carries a hardened steel bearing for the knife edge of the beam. The Brinell ball is removed and a block carrying a knife edge inserted in its place. The balance in position for calibrating a machine is illustrated in Fig. 1.

Application.—The calibration of an Aktiebolaget Alpha Brinell machine gave results shown graphically in Fig 2. The gage readings are plotted as ordinates for one curve and the load produced by the controlling weights for the other. The

actual load (as applied by the beam) is plotted as abscissae for both curves. As the controlling weights of this type of machine determine the pressure on the Brinell ball, their weight should be increased or decreased so that they just balance at the proper load when applied by the beam. The gage should also be calibrated to give the correct reading under the same conditions.

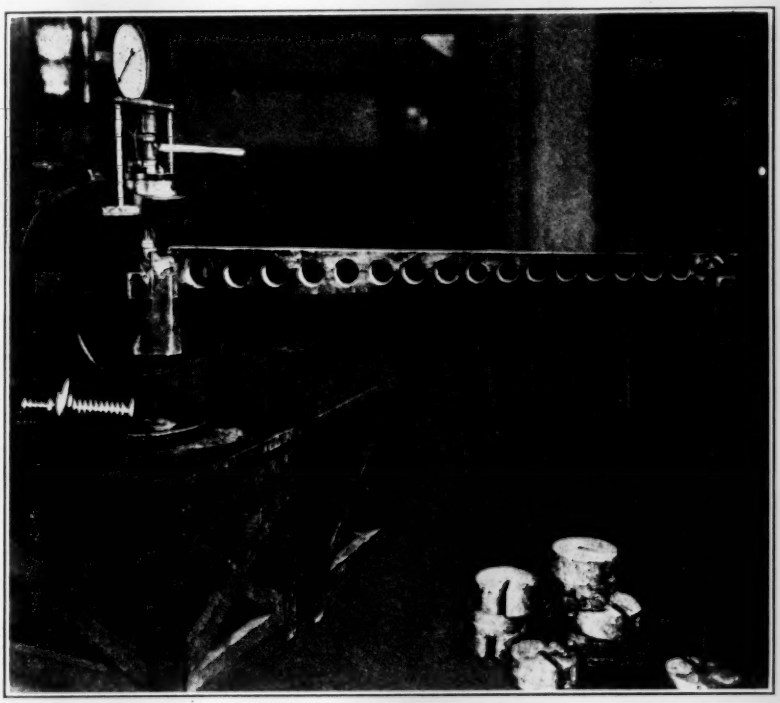


FIG. 1.—Beam in Position for Calibrating Brinell Machine.

The calibration of the Improved American Model Brinell machine is somewhat easier, as no controlling weights are used; it is only necessary to adjust the gages to give the correct reading of load applied by the beam. The results obtained on one of these machines are given in Fig. 3. The curve marked *A* was made with the piston in the highest working position, while that marked *B* is for a lower working position. The position

of the piston for the *A* curve is the same as it would be in testing hard material, where a shallow impression is made, while the position for the *B* curve is the same as it would be in testing soft materials, where a deep impression is made. The values of *A* are seen to be lower than those of *B*. This is probably

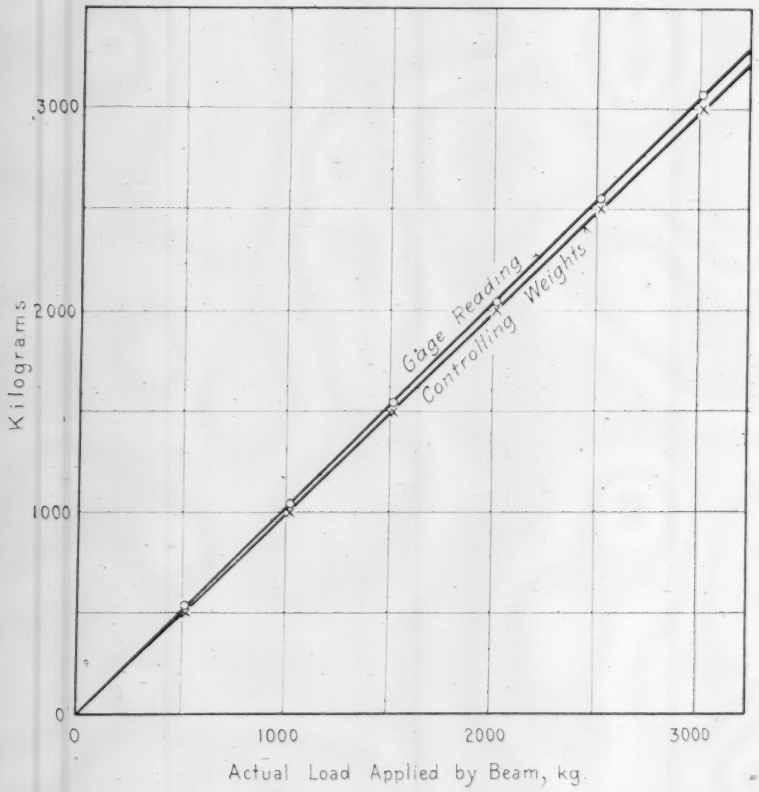


FIG. 2.—Correction Curve for Alpha Aktiebolaget Machine.

because the distance between the rubber diaphragm and the top of the piston is increased when the piston is at a lower point. The tendency of the rubber to curve at the edges is then greater. The working area of the piston would therefore be less, which would require a higher gage pressure to produce the same load

on the Brinell ball. The error introduced by this, however, is so small that it is negligible in ordinary commercial work.

Conclusion.—We have found this method to be an easy and convenient way of checking Brinell testing machines. There is no uncertainty as to the results, as they do not depend

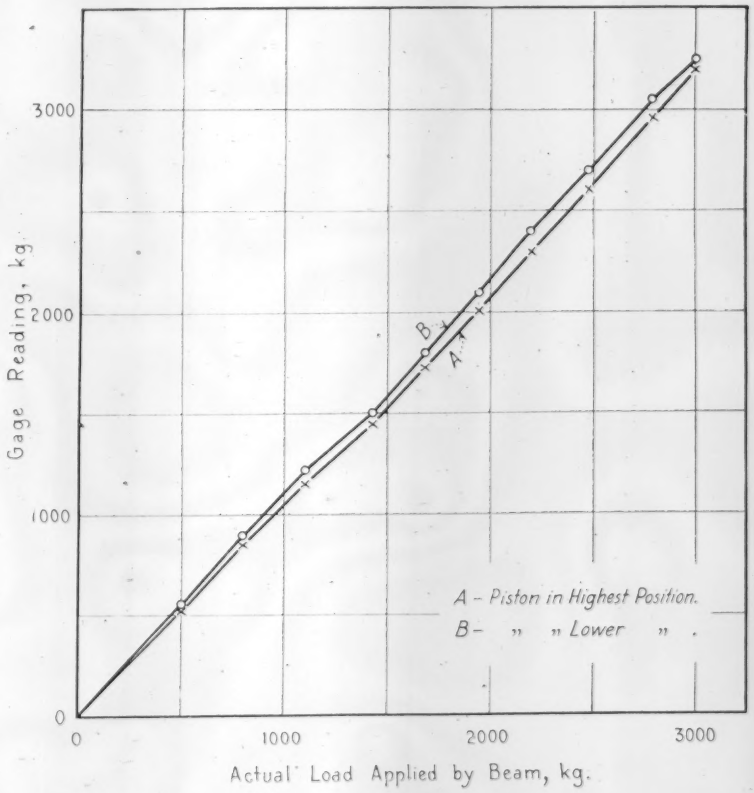


FIG. 3.—Correction Curve for American Model Brinell Machine.

on the comparison of readings. The beam may easily be taken to any machine suspected of giving incorrect results and the machine calibrated in a very short time. We have found that a periodic checking of Brinell machines is advisable and that this beam provides a satisfactory method of making this check.

DISCUSSION.

Mr. Boylston.

MR. H. M. BOYLSTON (*presented in written form*).—The method described by Jones and Marshall is indeed a simple and an interesting one. Numerous cases have come to the writer's attention where so-called "Brinell" machines failed to agree and where the discrepancy could not be traced to differences in the reading microscope. This method should dispose of such discrepancies very quickly and easily.

Perhaps the most interesting of the results obtained by Jones and Marshall is that given in Fig. 2, showing a correction curve for the machine made by Aktiebolaget Alpha, which is constructed after the original design and under the personal direction of Dr. J. A. Brinell whose name is now so familiar in connection with the testing of hardness by the ball method. Not only does the controlling-weight curve check with the new calibration method within a few kilograms but the apparent percentage of error is not more than about 1 per cent and probably even less. This percentage error if applied directly to the Brinell hardness number would mean an error of not more than six points in the hardest steels and about two points in the softest. As a matter of fact the makers of the Alpha Brinell machine guarantee an accuracy of 2.5 kg. for all loads up to 3000 kg., each machine being accurately tested by direct loading with weights before leaving the works. This would amount to an error of not more than 0.1 per cent. Thus it will be seen that the Alpha machine is practically self-calibrating if kept clean and free from rough usage.

Messrs. Jones and Marshall do not give the exact figures for their calibrations of the Alpha machine and it would be interesting to know how the actual figures compare with the accuracy claimed by the makers.

Their comparison brings out a point which is often overlooked in the use of this machine. The makers do not guarantee the gage readings, depending upon the direct weight method and the balancing of the beam for securing the proper pressure. The gage is added merely for the convenience of the operator,

to allow him to ascertain when the required weight is approximated, and the balancing of the beam then does the rest. It was furthermore never intended that the gage readings should be recorded but even in the case of the gage readings as shown in Fig. 2 the error is remarkably small. Mr. Boylston.

Incidentally, I might remark that there is only one real Brinell ball testing machine and that is the one which is made by Aktiebolaget Alpha, Stockholm, Sweden. Dr. Brinell has never given permission, to the best of my knowledge, to any other manufacturer for the use of his name in describing a machine for making hardness tests by the ball method, so that it is rather misleading to speak of a Brinell machine unless the one referred to is the original machine designed by Dr. Brinell and made by Aktiebolaget Alpha.

A-B·ALPHA·SUNDBYBERG

THE ACCURACY OF THE AKTIEBOLAGET ALPHA ORIGINAL BRINELL MACHINES.

In the following is given an extract of the correspondence between the American Society for Testing Materials, Philadelphia, Pa. and Aktiebolaget Alpha, Stockholm, Sweden, relating to a preprint dealing with "A new method for Calibrating Brinell Hardness Testing Machines" by Messrs J.L.Jones and C.H.Marshall, which was presented at the Society's Annual Meeting, June 1920.

In this paper the autors say that while making a series of Brinell tests which required a greater degree of accuracy than usual it was found in the Physical Testing Laboratory of the Westinghouse Electric & Manufacturing Co., East Pittsburg, Pa., that results obtained by two different machines did not agree. Although the loads recorded by the gages were identical the diameters of the impressions were not the same. The gages were therefore thought to be incorrect; but even after the gages had been carefully standardized, the different machines gave results which did not agree. A contrivance for checking was made, consisting of a lever balance and accurately adjusted dead weights, the multiplying ratio of the lever being known.

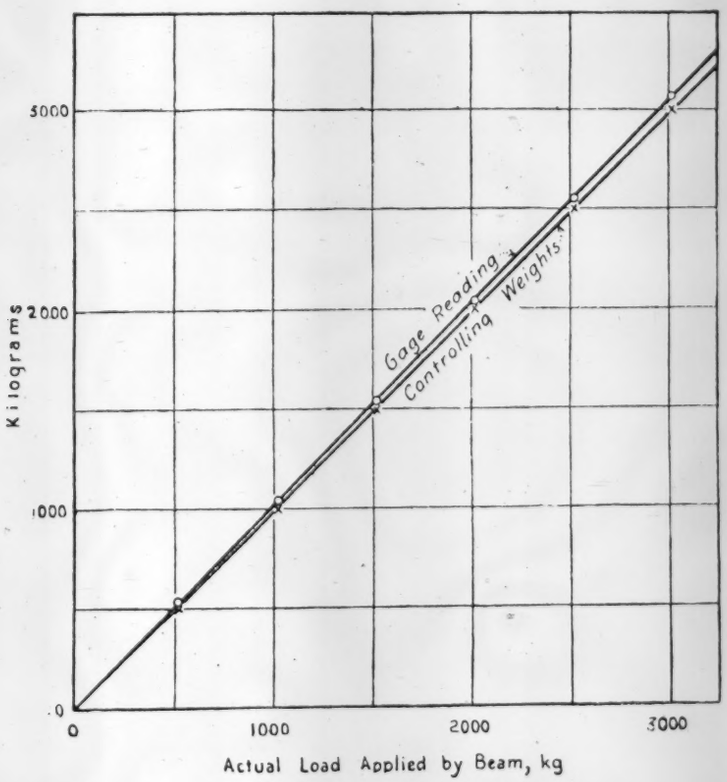


FIG. 2.—Correction Curve for Alpha Aktiebolaget Machine.

The calibration of an Alpha Machine gave results shown graphically in Fig. 2.

"As the controlling weights of this type of machine determine the pressure on the Brinell ball", the autors say, "the weight of the controlling weights should be increased or decreased so that they just balance at the proper load when applied by the beam."

The calibration of an "Improved American Model Brinell Machine", using no controlling weights, gave the results shown in Fig. 3, also copied from the autors' paper.

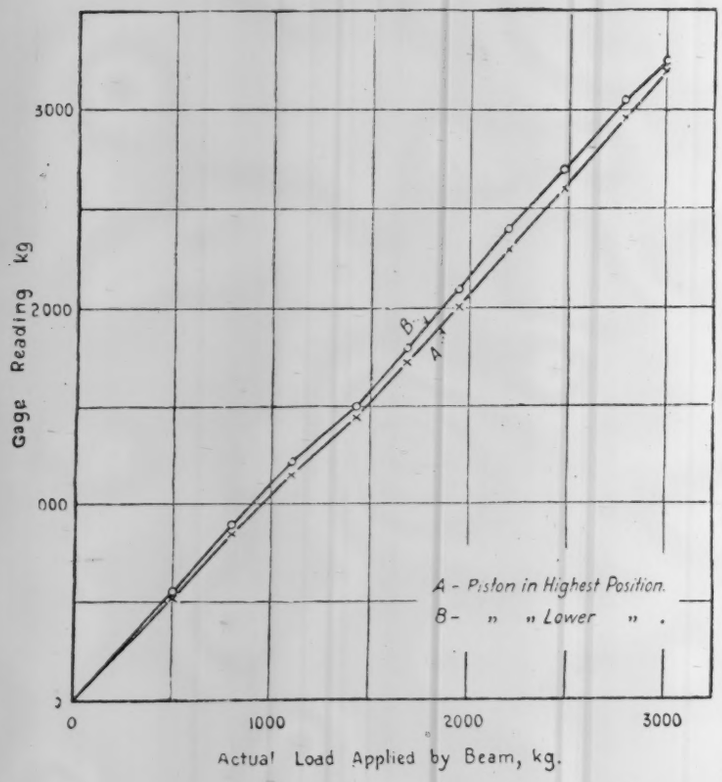


FIG 3.—Correction Curve for American Model Brinell Machine.

Discussing this paper, to which our attention was called unfortunately only some time after the Annual Meeting had been held, we wrote to the Secretary as follows:-

— — — "The rather fair "concordance which the "autors have obtained "with a machine of our "make, indicates that "they have carefully "made their experiments "and we feel sure that "the error yet found by "them (according to the "diagramm about 18 kg.) "is due to an error of "the testing machine "used for checking the "ratio of the lever. We "cannot concede that our "machines have any error "of this amount as every machine is carefully checked by means of accu- "rately adjusted dead weights up to its full capacity, usually 3000 kg., "without using any balance lever contrivance. As the accuracy depends on "so constant factors as are the two cylinderdiameters and the controll- "ing weights of the machines, one need not fear that the accuracy will "change as long as the machines are kept in working order and the con- "trolling weights are left intact.

"We therefore feel that it is our duty — and for this reason we "have made free to write you — to advise owners of "our Brinellmachines not to act according "to the suggestion of the autors "that 'the weight of the controlling weights should be increased or de- "creased, so that they just balance at the proper load when applied by "the beam.'

"They further say that "the gage should also be calibrated to give "the correct readings under the same conditions'. Commenting upon this "suggestion we beg to say, that however wrong a gage may happen to be "this will not impair the accuracy of the testing results in our machi- "nes. It would therefore be useless to calibrate it by means of the said "lever. The only object of the gage is to show how the pressure increa- "ses by pumping before the controlling weights are rising. If one appre- "ciate that the gage indicates exactly f.i. 3000 kgs. in the moment when "the weights are rising, it may of course be checked against these "weights."

In reply to this the Secretary wrote:-

"I duly received your letter of March 2nd discussing the paper by "Messrs Jones and Marshall,presented at our last Annual Meeting. I sub- "mitted your letter to Mr. Jones and I am quoting as follows from his "reply:-

"It was not our intention to be unfair to the makers of the Aktie- "bolaget Alpha Brinell Machine in any respect whatever. Their machine "is most admirably made and the workmanship on it is very much above the "average. However, with constant use we have found that even the Aktie- "bolaget Alpha machine will show wear. I regret that the diagram which "was mentioned in our paper and which shows an error in reading to "18 kg. was made on a machine that had been in use for a long period "without being repaired. We considered that the error to 18 kg. which we "found was not excessive for such work as we have been doing on the ma- "chine and a later examination showed that the controlling weights,which "are made of Cast iron, had been rather roughly handled and some of them "chipped."

"After correcting the above errors in the controlling weights and "cleaning the machine thoroughly, we found that an accuracy of 2'47 kg. "at a load of 500 kg. and 3'33 kg. at a load of 3000 kg. was obtained. - " -

"The chief difficulty which we have had with the Alpha machine is "that it shows some wear after a number of years' use, which is possibly "what could be expected. We tried to take care of this wear at first by "using a heavy steam cylinder oil, but this resulted in incorrect re- "sults in cold weather. By using a lighter oil, the leakage was exces- "sive past the 10 mm. ball, but by using two balls the leakage was "much reduced while the accuracy of the machine as checked by the beam "was improved. -

"A blueprint showing the recent check on our Alpha machine is sub- "joined." (Fig.4, page 4.) - - - - - - -

To this letter we replied as follows:-

"We would ask you to be kind enough to present our thanks to "Mr. Jones for the gentlemanlike manner in which he is doing justice to "us, which we much appreciate.- - - An error of 18 kg. is, indeed, not

"important at a load of "3000 kgs., but it far "exceeds the error sta- "ted in our pamphlet, "viz.:+- 2'5 kgs., being "the guaranteed accura- "cy.As we are quite sure "that every machine that "leaves our Works is of "the promised accuracy, "we felt it necessary to "object to the sugges- "tion in the paper by "Messrs Jones and Mars- "hall that the weight of "the controlling weights "should be increased or "decreased."

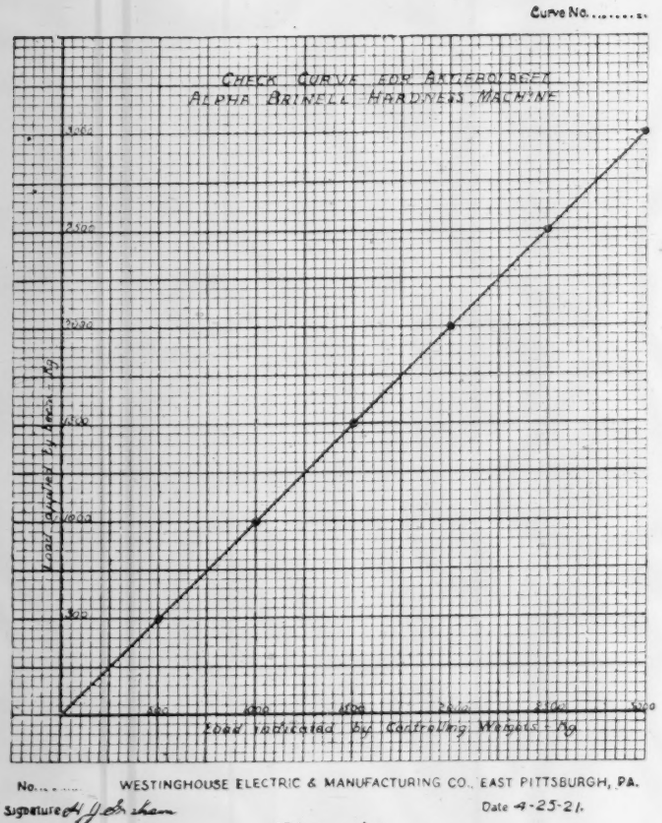


Fig. 4

"It may of course "be conceded theoretic- "ally that our machines "should show wear in "course of time with "frequent use, but in "practice we have never "been able to verify any "wear. We know that ra- "ther much oil is leaking through the small controlling cylinder when "only one ball of 10 mm. diameter is used, but this is the case even in "new cylinders and is therefore not due to wear. We are consequently "a l w a y s using t w o balls (See Directions for use.)

"- - - -

DUCTILITY TESTING MACHINES.

By Thorsten Y. Olsen.

The patent records show that testing machines and methods for cupping sheet metal to determine its drawing quality have been in use in one form or other for many years. Cupping tests have been made at various times in machines of varying construction, thus showing a need for such a test. The difficulty with all such testing machines has been that they were not made to give complete data on ductility. The ordinary sheet-metal test for determining drawing quality merely cupped the sheet under prescribed conditions and noted the depth of cup. Means had been proposed, though never used, for measuring the power necessary to produce such a cupping.

The author a few years ago came to the conclusion that such a test to be effective must weigh the direct pressure necessary to distort the material. With this object in mind a ductility testing machine was developed as illustrated in Fig. 1.

The sheet metal to be tested is placed in the slot under the upper hand wheel and over the die, preferably in the form of a disk 3 in. in diameter. The upper wheel is then screwed tight and again relieved to give the clearance desired for drawing to 0.001 in., as may be noted on graduated scale. Pressure to cup the metal is then applied by the hand wheel shown at the left which actuates a worm gear running in an oil bath and a large thrust ball bearing so as to reduce the manual effort to a minimum. The amount of cupping to cause fracture is noted on a dial at the extreme top and is read directly to 0.001 in. The point of fracture and the behavior of the metal may be noted by directly observing the specimen. The pressure to cause cupping is weighed directly by means of a confined liquid and a gage, which in this size of machine reads to 12,000 lb. The above machine is very compact and convenient to operate and will test metal up to $\frac{1}{16}$ in. in thickness. For heavier material a larger machine is necessary.

A machine of this type made so as to autographically record the relations between the pressure and amount of cupping is now being developed.

A few years ago an attachment was built to fit universal testing machines. Fig. 2 shows such an attachment, the upper portion being fitted to the lower surface of the moving crosshead while the lower portion rests on the weighing table.

FIG. 1.—Ductility Testing Machine.

The specimen or sample to be tested is placed in the machine in a manner similar to that in the machine previously described. Clearance for drawing is set as desired, and the pressure is applied by the testing machine. The amount of cupping is noted on the dial at the base and the point of fracture by viewing the specimen through a mirror. The pressure is weighed directly on the scale beam of the testing machine.

This attachment is adapted to testing heavier sheet metal, as the average testing machine has ample capacity to apply and weigh the load. Sheets up to a maximum of $\frac{3}{8}$ in. in thickness have been tested.

Sometimes, owing to differences in personal observation and speed of operation, there arises a question as to where

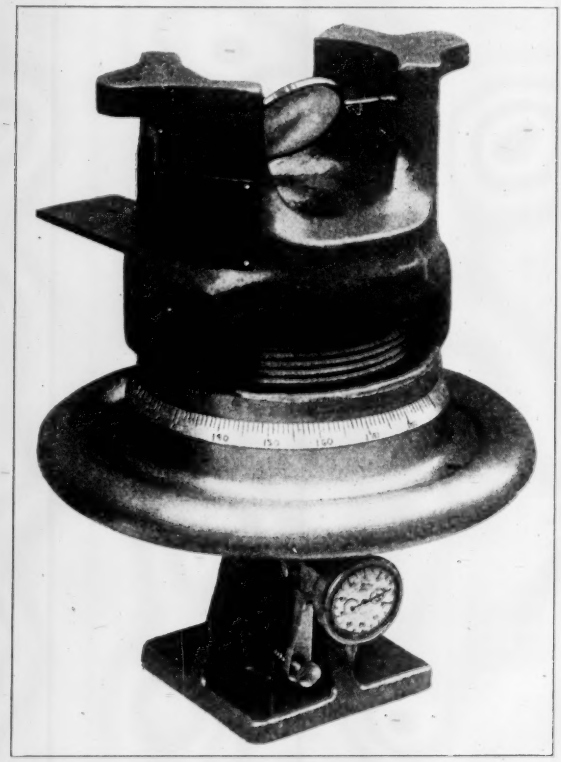


FIG. 2.—Ductility Testing Attachment for Universal Testing Machine.

rupture of the cup occurs. In either the machine or the attachment here described this point can readily be noted from observation of the pressure which immediately falls when rupture occurs.

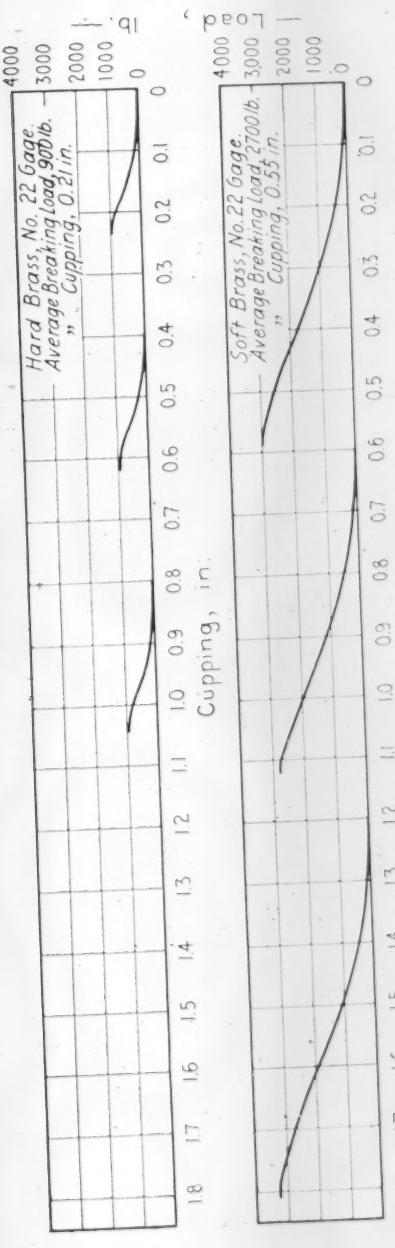

Hard Brass, No. 22 Gage.
Average Breaking Load, 900 lb.
" Cupping, 0.21 in.
Soft Brass, No. 22 Gage.
Average Breaking Load, 2700 lb.
" Cupping, 0.55 in.
Load, lb.
4000
3000
2000
1000
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8
Cupping, in.

FIG. 3.—Autographic Records of Ductility Tests on Hard and Soft Brass, No. 22 Gage.

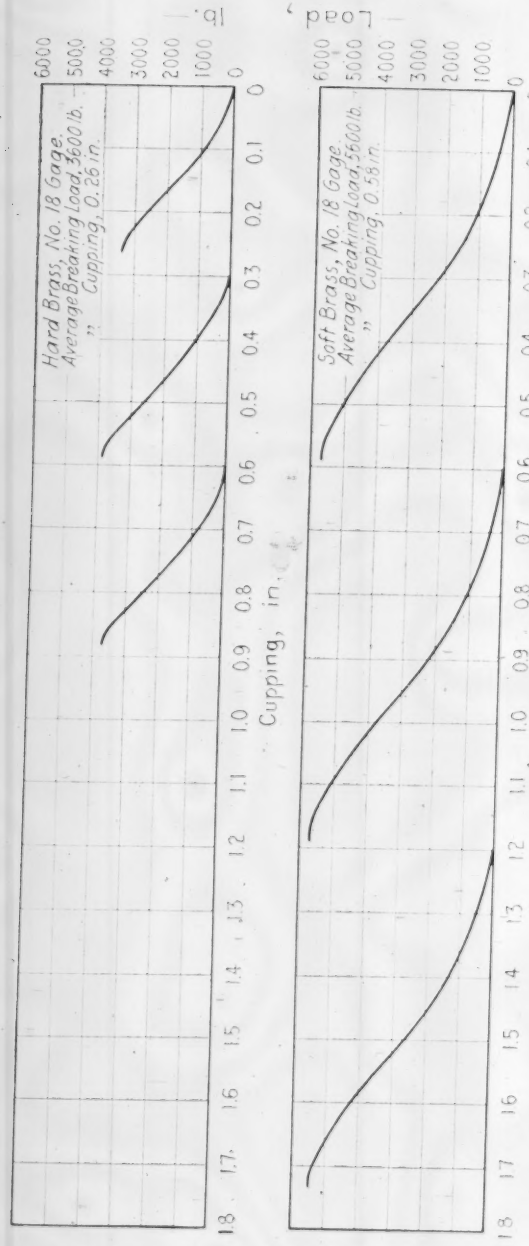

Hard Brass, No. 18 Gage.
Average Breaking Load, 3600 lb.
" Cupping, 0.26 in.
Soft Brass, No. 18 Gage.
Average Breaking Load, 5600 lb.
" Cupping, 0.58 in.
Load, lb.
Cupping, in.

FIG. 4.—Autographic Records of Ductility Tests on Hard and Soft Brass, No. 18 Gage.

Figs. 3 and 4 are autographic records taken from an automatic and autographic universal testing machine using the attachment as here described. These particular tests were made on various gages of soft and hard sheet brass ranging from No. 18 to No. 26 gage. Three tests were taken from each sheet to establish an average and show the uniformity in results so obtained.

To demonstrate the value and need of weighing the pressure in a test of this kind, mention might be made of a case that came to the author's notice only a short time ago. Two supposedly similar samples of sheet steel of different makes were subjected to test. The amount of cupping to point of fracture was practically the same, but the pressure to cup the one steel was twice that of the other. The test without weighing the pressure would pass both lots of material. But the work of drawing or power consumed in producing a given distortion in one case would be double that in the other. The strain on the presses would be also double, possibly sufficient to injure them if they were running close to capacity on the low-pressure steel.

Such a possible break-down might be entirely avoided by a test for ductility based on the load required for cupping.

DISCUSSION.

Messrs. Price and Chamberlin.

MR. W. B. PRICE AND MR. C. G. CHAMBERLIN (*presented in written form*).—In connection with the paper on Ductility Testing Machines, by T. Y. Olsen, it may be of interest to members of the Society to learn that in the testing laboratory of the Scovill Manufacturing Co. we have developed independently a ductility testing machine similiar to that described by Mr. Olsen.

A description of the combination of the Erichsen Machine with the Olsen Testing Machine and the development of a new factor, pounds per inch, for annealed material, follows:

The testing by our laboratory of sheet metal for Erichsen ductility has been undergoing a process of evolution since the installation of our recently built equipment which is operated on the table of an Olsen testing machine. The apparatus was planned (November, 1918) and constructed in our plant by Mr. H. H. Bagg, head of the Scale Department. It was completed in January, 1919, and immediately put in use. The machine and its operation may be briefly described as follows:

Comparative dimensions and weight, including attached extensometer:

SCOVILL.	OLSEN.
Length, 13 in.	Length, 11 in.
Breadth, 10 "	Breadth, 11 "
Height, 18 "	Height, 16 "
Weight, 78 lb.	Weight, 75 lb.

A compression plate carried by the lower crosshead of the Olsen, on the weighing table of which our attachment is placed, forces the cupping tool vertically downward into the material being tested. The top of the plunger against which the compression plate bears, carries a rigid arm which transmits the depth of cup to an extensometer (ratio 4:1) graduated to 0.01 mm. upon which it is registered. The progress of the test is observed through a mirror and the point of fracture noted.

A view of the apparatus is shown in Fig. 1.

Of course the valuable feature of this combination of testing and ductility machines, is the ability to weigh the load required

to fracture the material, this being registered on the scale beam, likewise the pressure necessary to reach the yield point as determined by the drop of the beam or to cup to any desired and uniform depth previous to fracture, all of which variations we

Messrs. Price and Chamberlin.

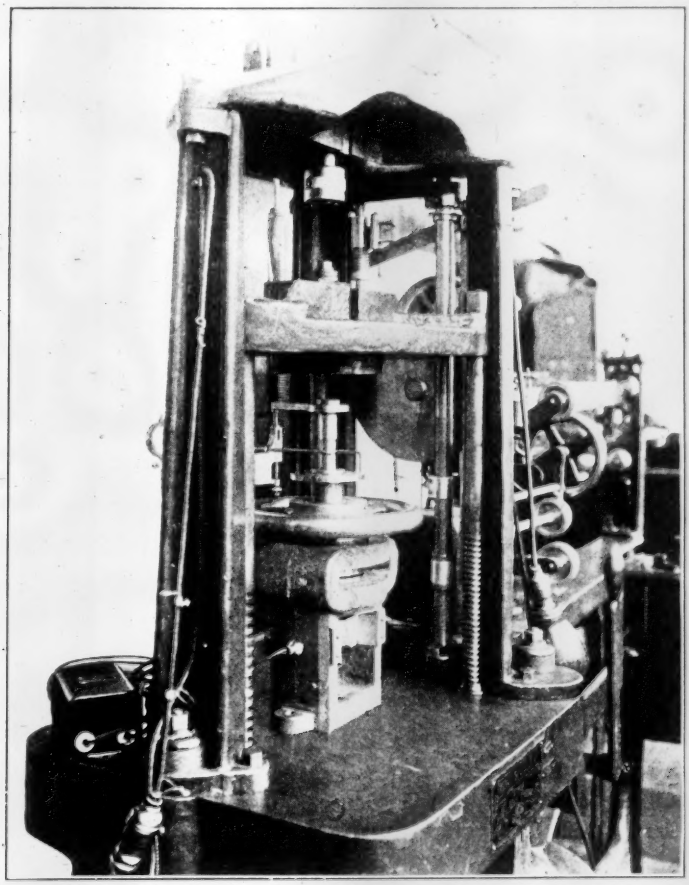


FIG. 1.—Scovill Ductility Testing Machine.

have made use of. In connection with this load weighing it will be apparent that the final drop of the beam at or just prior to actual rupture furnishes a reliable and uniform indication of correct depth reading. To render this more delicate we cut

Messrs. Price and Chamberlin.

down the speed somewhere in the vicinity of the yield point to allow a safe margin prior to fracture.

Sometime after the substitution of this attachment for the type of Erichsen Sheet Metal Tester commonly in use, we noticed in the latest catalogue of the Tinius Olsen Testing Machine Co. that the same general scheme had been made use of by them, the only essential difference being that in their equipment the drawing tool is forced vertically upward into the metal being tested while in ours the movement is downward.

This vertical movement, the result of direct push of the drawing tool shaft through a sleeve of smooth bore, has marked and easily discernable advantages over the Erichsen type of transformed horizontal forward movement generated by rotation. Due to more complicated design with increased possibilities of wear, and presence of back-lash, to the fact that the point of fracture is fully reached before the depth is read and to other apparent differences between the two machines, the old hand-power type may record slightly higher readings. This is owing to the fact that as soon as the contact between the outer and inner threads, upon which the Erichsen depends, becomes a little worn, as it soon must, the plunger will advance with a slight spiral movement which will draw a little more material into the cup.

We have shown that Erichsen ductility values for gages of annealed metal below 0.060 are as dependable as, and comparable with, Brinell hardness numbers for gages 0.060 and above. This concordance is best shown and expressed by the use of a factor which we have designated pounds per millimeter which can be easily converted to pounds per inch and which is of course obtained by dividing required pressures in pounds by resulting cup depths in millimeters. This factor for a given gage of annealed metal is especially valuable in its inherent ability to compensate for, and reduce to common basis of comparison any local irregularities of stock which, although often real inequalities in structure, are sometimes but hidden flaws. Between these two classes the Erichsen cup depth reported alone is not able always to differentiate on account of its extreme and peculiar sensibility.

Our attachment has been fitted with a set of regulation Erichsen drawing tools each furnished with special dies. These

Messrs. Price and Chamberlin.

comprise the standard parabolic tool, the 10 mm. tool (diameter of standard Brinell ball) for metal down to 1 in. wide, the 2.3 mm. tool for metal down to $\frac{5}{16}$ in. wide and the extra parabolic tool for cartridge cups. We are having also prepared a set of dies for drawing wire with the standard tool. For all of the wire upon which we intend to initially experiment we already have tensile results.

An adaptation of our attachment suggested itself to us in connection with the ductility testing of wire. By means of another special tool and die, we are enabled to make a transverse test on wire and sheet metal over a clear span of 2 in., the pressure being centrally applied through a plunger of standard proportions, though having, of course, reduced dimensions. In the case of the sheet metal, this 2 in. is measured from chord to chord of the circular die opening, the subtended solid segments of which provide uniform points of support for the tested strip. As a result of this transverse test, we hope to show instructive differentiation in our pound-per-inch factor between successive reductions of metal beyond the annealed state, to supplement the ductility values of the same factor for annealed material. We also expect to develop interesting ratios between strips thus transversely tested, cut longitudinal with the direction of rolling and those cut transverse to the same. Finally, we aim to find definite relations existing between this combined series of values, and a series of longitudinal and transverse tensile tests on similar cross-sections of the same stock. For wire and annealed metal, we will have both ductility and transverse tests on the same material, expressed in pounds per inch.

Thus, to date, may be summarized our development and expansion of the testing of sheet metal as performed by the modified Erichsen machine, and which we hope will form the basis for a paper to be presented at the next annual meeting of the Society.

A NEW TYPE OF AUTOMATIC CEMENT TESTER.

By Thorsten Y. Olsen.

The tension test is in universal use in the testing of cement owing to the facility with which the small specimens used in the test are made and tested. Such a test will undoubtedly continue to be an essential test for cement for years to come.

The customary type of cement tester in use for many years, and in use to-day, is what is known as the automatic shot type which utilizes a flow of shot to apply the load to the cement briquette. The shot required to break the specimen is weighed on a scale, and the breaking load of the briquette thus indicated. This type of cement tester is a successful one, but the shot requires considerable handling by the operator for each test made, with a consequent loss of shot. The rate of flow and cut-off of shot is also liable to vary somewhat, depending on the condition of the shot, the container, and the design and adjustment of the cut-off mechanism.

A new type of construction in testing machines has been developed by Mr. Harry W. Boyd, and while this construction is applicable in many ways to testing various materials, Mr. Boyd has first utilized the principles of construction in the development of a new type of machine for testing cement. The machine is illustrated in Fig. 1, and will be known as the Olsen-Boyd Automatic Cement Tester. In general design or outline, this machine very much resembles the ordinary type of automatic shot-cement tester, with the one difference that a liquid is used in place of shot.

The actual work of the machine is accomplished through the medium of a suspended weight which applies the load as shown in Fig. 1. This weight and the lever to which it is attached, and which applies the load to the briquette, is set in motion by turning a thumb-screw valve, thus releasing the liquid within the vertical cylinder shown. As the weight moves down, the cement briquette is placed in tension through the action of the weighing system. The load is indicated on the dial shown to the extreme left of the machine.

To make a test in this machine, the weight lever is raised by hand to the top position with the thumb-screw valve closed, and the pointer on the dial set to zero. The briquette is then placed between clips; initial load is applied by a hand wheel below the lower clip; and the thumb-screw valve is opened, thus applying

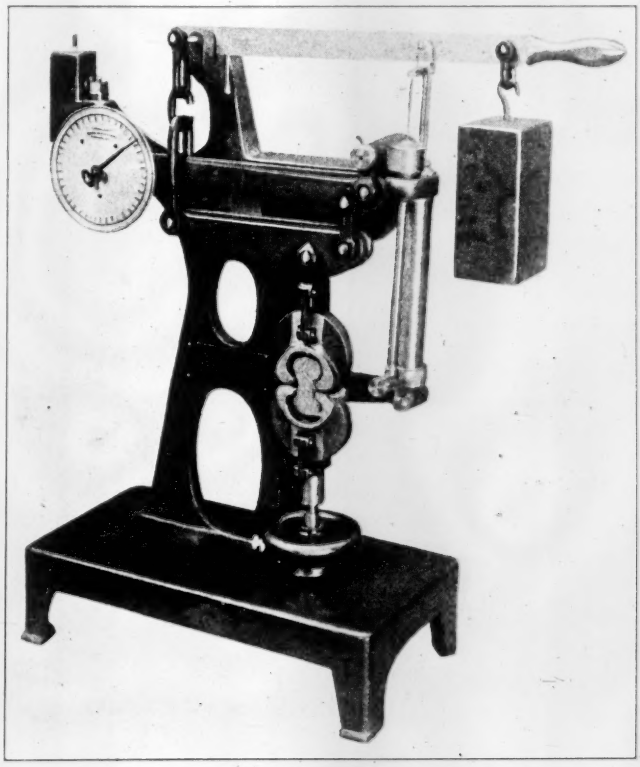


FIG. 1.—The Olsen-Boyd Automatic Cement Tester.

load to the briquette until fracture occurs. The breaking load is read directly from the pointer on the dial.

The flow of the liquid is so controlled that it applies a uniform load of 600 lb. per minute. The registering of any load applied is positive and instantaneous, the pointer on the dial remaining at the maximum point when the briquette breaks.

After the rupture of the specimen it is merely necessary to close the thumb-screw valve, raise the weight lever, and return the pointer on the dial to zero, for the machine to be ready for the next test.

This cement tester is thus not only very accurate and reliable, but is also the most easily and quickly operated of any in use at the present time.

A NEW METHOD OF TESTING GALVANIZED COATINGS.

By Allerton S. Cushman.

It is customary to purchase galvanized sheet metal and wire to specification governing the weight of spelter in ounces per square foot. In dealing with sheet metal the weight of spelter is recorded for both sides so that a 2-oz. coating means 1 oz. on each side. In dealing with wire or with sections of irregular shape, the weight of coating is variably reported as may be especially specified in advance. In 1915, J. A. Aupperle[1] proposed the hydrochloric acid-antimony chloride method for stripping $2\frac{1}{4}$-in. squares of sheet metal and further adapted the method for wire by calculating and tabulating ounces per square foot from the gram loss on unit lengths of wire of any given diameter and gage. For articles of irregular surface, the method is not always adapted. Considering the estimation of weight of spelter coating on flat sheet metal, the Aupperle method is by far the quickest and most accurate of all methods heretofore proposed, when the measured $2\frac{1}{4}$-in. flat samples are once in hand. In fact, recent work has shown that even the addition of antimony chloride is a superfluous precaution and that sufficiently accurate results can be obtained by stripping with straight, concentrated hydrochloric acid.

The principal drawback, however, to all previously used methods of testing sheet metal lies in the practical difficulties encountered in obtaining the flat measured test pieces ready for stripping in acid. This difficulty is encountered especially in the field whenever it is necessary to check up the weight of spelter coating on corrugated culverts. In such a case it is necessary to attack one end of a selected number of culverts in a consignment with drill and hacksaw, in order to remove samples. These corrugated samples must then be conveyed to the nearest testing laboratory where a press of sufficient power is available to flatten out the sections. These must next be sheared or machined to

[1] *Proceedings*, Amer. Soc. Test. Mats., Vol. XV, Part II, p. 120 (1915).

$2\frac{1}{4}$-in. squares, preparatory to going to the laboratory where they are to be weighed and stripped. All this consumes time and labor and in addition some of the zinc coating may be flaked off during the flattening and machining operations.

Another great disadvantage lies in the fact that the culverts sampled are mutilated and damaged, which is no inconsiderable item when large culverts are under consideration. Moreover, the sample must be taken from the end section only, unless the culvert is to be utterly ruined. In at least one contested case of rejection of a lot of culverts which came under the author's observation, it was found that the middle sections of the culverts were made of cheaper metal than the ends. All these facts accentuated the great desirability of a method of testing, which would, if such a thing were possible, fulfil the following specifications:

1. The test should determine weight of coating on any part of the surface of a flat sheet, corrugated sheet, or finished culvert that it is desired to explore.

2. The test should not destroy or mutilate the sheet or culvert under examination.

3. The test should be applicable to field conditions where laboratory facilities are not available.

4. The test should be applicable for testing wire and any small galvanized pieces.

5. The test should be at least as accurate as previous methods which have been used for determining weight of spelter coatings.

Experience with the Aupperle test had shown that all the zinc on the test piece was stripped in less than a minute, the equivalent hydrogen coming off with a rush and the end point of the reaction being sharply marked by the sudden cessation of the gas flow. It was further observed that even if the antimony chloride was omitted, the end point was still fairly sharp so that it was easy to distinguish the moment when the zinc was all in solution and the iron or steel base began to be very slowly attacked by the acid. In fact, Mr. Aupperle had himself reached the conclusion that in making the regular stripping test in daily practice the addition of antimony chloride was unnecessary and superfluous, since it was easy to tell the point in time when the

test piece should be lifted from the acid bath for rinsing, drying and weighing.

This experience led the author to believe that if it were possible to collect the hydrogen gas given off from a known area of any surface, the weight in ounces per square foot could be at once determined. Preliminary calculations showed that if such a method of testing could be worked out, any error due to slight

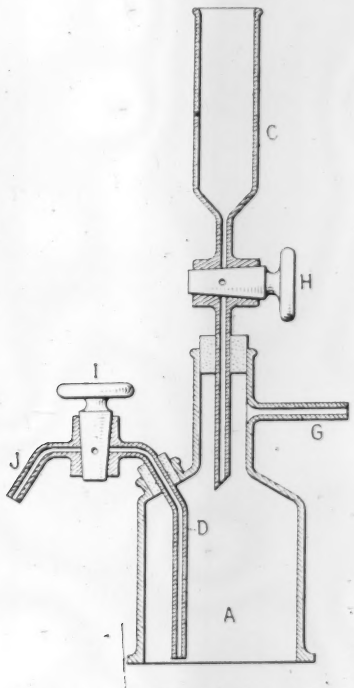


FIG. 1.—Apparatus for Testing Galvanized Coatings.

variations in the volume of gas collected, owing to variable temperature and pressure, would be practically negligible when translated into ounces per square foot of zinc. On the other hand, the area of any spot under test must be accurately known, as error due to unknown or variable area would be considerable.

With these considerations in mind, experiments were begun, at first on flat galvanized sheets. The first apparatus made was

constructed entirely of glass as shown in Fig. 1. Although this glass apparatus has now been entirely abandoned for a much simpler and more practical device, it is nevertheless shown here as the first step in the evolution of the test as it is now carried out. The tests were made by smearing the bottom rim of the vessel *A* with desiccator grease and pressing it down firmly on the surface of a galvanized sheet. A rubber delivery tube not shown in the figure connected with the gas outlet tube *G* with a water displacement burette. When all was ready, exactly 25 cc. of hydrochloric acid - antimony chloride solution was placed in the thistle tube *C*, stopcock *I* being closed; stopcock *H* was then opened just long enough to permit the acid in *C* to run into vessel *A*. The reaction was over in about 30 seconds after which it was necessary only to read the volume of hydrogen corrected for the volume of acid that entered the system. The area of the spot covered by vessel *A* being known, the number of cubic centimeters of hydrogen multiplied by a factor gave the ounces of zinc per square foot. The burette could be calibrated to read directly in ounces per square foot.

After a test was completed, water was let down through *C* and gently blown out at *J* until the residual acid and zinc chloride were all rinsed out. The apparatus could then be lifted and the bare spot on the sheet cleaned up by wiping and rubbing over with a little gasoline. The known cross-section area of the base of vessel *A* could then be checked up if desired with the actual area of the bare spot by the use of a planimeter. It is obvious that if the desiccator grease used as a seal spread on the surface it might protect some of the zinc around the circumference from the action of the acid; although when the greasing was carefully and expertly done, error due to this cause was usually negligible.

Very concordant results on flat sheets were obtained with this apparatus when all the conditions of test were fairly constant, although the actual variations in weight of coating on different spots on any given sheet always introduces an unknown factor, no matter what kind of test is used. It was soon found, however, that owing to the comparatively large volume of cold air in the vessel *A* which had to be displaced by the hot hydrogen evolved by the reaction, considerable errors were liable to occur. It was immediately obvious that the volume of *A* must be reduced

and if possible all the air in the apparatus be displaced by water before any acid was allowed to enter from C.

The objections to an all-glass apparatus were numerous. It was expensive, fragile (and therefore subject to breakage) and could not be modified as improvements suggested themselves. For these reasons the all-glass apparatus was at once abandoned. It was next suggested that hard-rubber rings closed with ordinary soft-rubber perforated stoppers could be substituted for glass. Hard-rubber tubing of about $2\frac{1}{2}$-in. diameter could not, however, be obtained. Experiments were therefore projected with lead pipe rings. This material had the advantage that it could easily be cut and shaped to fit the contours of a corrugated surface but the walls of the lead ring tubes were so thick that it was found difficult to control the surface area attacked by the acid.

In the meantime, Mr. J. A. Aupperle and Mr. H. E. Brooks of the Research Department of The American Rolling Mill Co., who were cooperating with the author, reached the final solution of the problem by welding up rings of tinned sheet-iron of No. 22 gage. It was further discovered that the plastic clay known as Plastaline, sold by artist supply houses for modeling, could be used to make an acid-tight dam or joint around the base of the rings when the apparatus was set down in place on the galvanized surface to be tested. These expedients have made possible the development of a rapid and easy test which fulfils all the specifications as outlined above. A complete testing outfit as finally developed consists of several tinned iron rings, a No. 12 two-holed rubber stopper, a glass thistle tube with ground glass valve, a graduated water displacement burette and a couple of feet of soft-rubber tubing. The metal ring for flat sheets is ground true at the bottom and preferably made with a sharp beveled edge in order to cover a sharply defined area. Another ring is convoluted on the bottom for use on flat corrugated sheets, while other rings are cut and ground with emery to fit the corrugations and curvatures of finished culverts of the various sizes in use. Armed with this simple apparatus, an inspector can now quickly determine the weight of coating on any portion of the surface of a sheet or culvert. The stripped and thoroughly pickled test spots can be re-galvanized in the

field by dusting them over with a mixture of granulated zinc and zinc chloride and heating with a small plumber's blow torch. The modified apparatus as used in this test is shown in Fig. 2.

The following report from the Research Department of

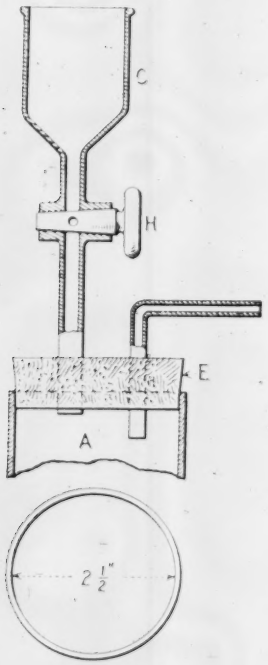


FIG. 2.—Improved Apparatus for Testing Galvanized Coatings.

The American Rolling Mill Co. presents the experimental data and proves the accuracy of the method:

"The tester used for the experiments was a tinned No. 22-gage Ingot Iron Ring, $2\frac{1}{2}$ in. in inside diameter and $1\frac{1}{2}$ in. high. A No. 12 two-hole rubber stopper was used, holding the glass-stoppered filling tube, and the glass exit tube. This exit tube was connected to the gas receiver. An inverted 500-cc. graduated cylinder answers this purpose well enough.

"In conducting the tests, the ring was held in place and sealed with 'Plastaline.' The apparatus was then filled with water, the glass exit tube being at its highest point so that all air would be displaced by water. The exit tube is pushed down to a point just above the sheet and the rubber tubing connected so that gas may be collected in the gas receiver. About 30 cc. of concentrated hydrochloric acid (sp. gr., 1.20) are placed in the filling tube and about 10 cc. allowed to enter the apparatus in order to generate enough gas to displace the water. Three cc. of 5-per-cent antimony chloride solution made up with concentrated hydrochloric acid are added to the rest of the hydrochloric acid. As soon as gas appears in the exit tube, the tube

TABLE I.—RESULTS OF TESTS ON THE GALVANIZED COATING ON FLAT SHEETS.

Cushman Test	(1) 1.19 (2) 1.37	(3) 1.13 (4) 1.18	(5) 1.14 (6) 1.13	(7) 1.12 (8) 1.16	(9) 1.21 (10) 1.17	(11) 1.32 (12) 1.26	(13) 1.05 (14) 1.07	(15) 1.40 (16) 1.31
Average	1.28	1.15	1.14	1.14	1.19	1.29	1.06	1.36
Regular Test	1.32	1.07	1.26	1.14	1.22	1.30	1.15	1.45
Difference between Cushman and Regular Test	−0.04	+0.08	−0.12	None	−0.03	−0.01	−0.09	−0.09

	Minimum.	Maximum.	Average
Area of spots in sq. in	5.20	5.35	5.27
Factor for cc. H to oz. per sq. ft	0.00258	0.00266	0.00262

Variation from using above factors, 0.04 oz. per sq. ft.

The figures given in the above table of the tests upon the detailed spots are in ounces per square foot of actual surface, or the coating upon one side of the sheet. To obtain figures for ounces per square foot of sheet surface as is ordinarily given, the above figures should be doubled.

The maximum variation between the doubled figures given above and the actual weight of coating upon both sides of the sheet is 0.30 oz. per sq. ft., the majority of figures being less than 0.10 oz. per sq. ft.

is raised until flush with the cork and the rest of the acid admitted to the apparatus.[1] When the evolution of hydrogen gas has ceased or only a bubble of gas comes every few seconds, the apparatus is filled with water to displace the gas. The gas is measured at 20° C., with the water inside the cylinder the same level as the water outside the cylinder. The number of cubic centimeters of hydrogen at 20° C., multiplied by the 'Factor,' will give the weight of the spelter coating.

"The rings used on flat corrugated sheets and on formed culverts are cut to fit the various shapes and sizes of culverts, any inequalities being overcome by sealing with plastaline.

[1] An improvement has been made in the apparatus which makes it unnecessary to change the adjustment of the exit tube.

"From detailed tests upon a flat sheet, corrugated sheet, and 12-in. culvert, the 'factors' for weight of coating were obtained, and the maximum error in the determination due to the variation in the apparatus determined, and its comparison with the results obtained by the regular hydrochloric acid - antimony chloride method, using $2\frac{1}{4}$-in. square samples cut from the sheets, and the weight of coating determined by weighing.

"*Check Upon Preliminary Calculations.*—Calculations based upon figures given in the Smithsonian Institution Tables gave the following data:

0.00272	g.	of	Zinc	will	produce	1	cc.	of	H	at	20°	C. and 760 mm.
0.2720	"	"	"	"	"	100	"	"	"	"	"	"	"
0.5440	"	"	"	"	"	200	"	"	"	"	"	"	"
0.8161	"	"	"	"	"	300	"	"	"	"	"	"	"
1.0881	"	"	"	"	"	400	"	"	"	"	"	"	"
1.3602	"	"	"	"	"	500	"	"	"	"	"	"	"

"Experiments performed by placing the above indicated amounts of pure zinc shot upon a glass plate and running tests

TABLE II.—RESULTS OF TESTS ON THE GALVANIZED COATING ON CORRUGATED SHEETS.

Cushman Test	(1) 1.21 (2) 1.21	(3) 1.01 (4) 1.31	(5) 1.10 (6) 1.47	(7) 1.16 (8) 1.40	(9) 1.10 (10) 1.47	(11) 1.28 (12) 1.48	(13) 1.16 (14) 1.38	(15) 1.30 (16) 1.36
Average	1.21	1.16	1.28	1.28	1.28	1.38	1.27	1.33
Regular Test	1.23	1.20	1.29	1.33	1.32	1.29	1.42	1.45
Difference between Cushman and Regular Test	−0.02	−0.04	−0.01	−0.05	−0.04	+0.09	−0.15	−0.12

	Minimum.	Maximum.	Average
Area of spots in sq. in	5.50	5.62	5.57
Factor for cc. of H to oz. per sq. ft	0.00246	0.00251	0.00249
Variation from using above factors, 9.03 oz. per sq. ft.			

The figures given in the above table of the tests upon the detailed spots are in ounces per square foot of actual surface, or the coating upon one side of the sheet. To obtain figures for ounces per square foot of sheet surface as is ordinarily given, the above figures should be doubled.

with the Cushman tester, gave results which were correct to within 5 cc., in most cases being within 1 or 2 cc. In the calculations, 1 cc. of hydrogen at 20° C. was considered equivalent to 0.00272 g. of zinc.

"A 24-in. piece of No. 16-gage culvert stock, $27\frac{1}{2}$ in. wide was sheared into two 12-in. pieces, one piece being left flat and the other corrugated. On each, a series of eight sets of tests

were run, each set consisting of two Cushman spots with a regular test between each one. The regular test consisted in cutting out a $2\frac{1}{4}$ in. square piece, and determining the coating by Aupperle's hydrochloric acid - antimony chloride method, the weight of coating on the top side being determined by coating the bottom side with shellac. The weight of coating on the bottom side was later determined in order to get the total coating on both sides, so as to compare this figure with the one obtained by doubling the figure given by the Cushman test.

TABLE III.—RESULTS OF TESTS ON THE GALVANIZED COATING ON A 12-IN. CORRUGATED CULVERT.

		(2) 1.68			(6) 1.50				(10) 1.53		
		R. T.			R. T.				R. T.		
(1)	1.52	1.51	(3)	1.58	(5) 1.58	1.43	(7)	1.38	(9) 1.31	1.32	(11) 1.28
		Av. C. T. 1.59				Av. C. T. 1.49				Av. C. T. 1.33	
		(4) 1.58				(8) 1.50				(12) 1.21	
		DIFFERENCE BETWEEN REGULAR AND CUSHMAN TESTS.									
		+0.08				+0.06				+0.01	

	Minimum.	Maximum.	Average.
Area of Spots: Not Corrected (Calculated) sq. in.	5.60	5.72	5.70
Area of Spots: Not Corrected (Planimeter) sq. in.	....	....	5.70
Correction due to curvature (Planimeter) sq. in.	....	....	0.10
Assumed correct Area of Spots sq. in.	....	....	5.60
Factor for cc. H to oz. per sq. ft. (Actual Surface)	0.00247	0.00250	0.00247

Variation from using above factors, 0.02 oz. per sq. ft.

Figures given are oz. per sq. ft. of coating on actual surface; for sheet surface double these figures.
Figures in ( ) are numbers of spots.
R. T. means results of Regular Test on $2\frac{1}{4}$-in. square sample from culvert.
Av. C. T. means Average of results of the four surrounding Cushman tests.
Nine corrugated ridges used in making this test.

"*Flat Sheet.*—Inspection of the test data (Table I) for the flat sheet will show that the weight of coating upon the galvanized sheet varied considerably, but that the average of the two Cushman spots was very close to the figure given from the regular test conducted on the piece taken between them. It is believed that the greatest variations are not due to error in the apparatus but to the variation of coating on that particular portion of the sheet. The variation in area of the spots, which was feared would cause a considerable error, is very small and in the 16 tests run would cause only a maximum error of 0.04 oz. per sq. ft., or an average error of only 0.02 oz. per sq. ft.

"*Corrugated Sheet.*—Inspection of the data for this test

(Table II) will show the same conclusions as for the flat sheet. The tests were made upon the culvert ridges, and the areas determined with the planimeter from tracings of the spots made upon transparent paper.

"*12-in. Culvert.*—After starting this test, the culvert was found to be one from a special test, with a very heavy coating, and, therefore, more variation of coating than would be found upon a culvert having a 2-oz. coating. The results, however could not be more satisfactory. See Table III.

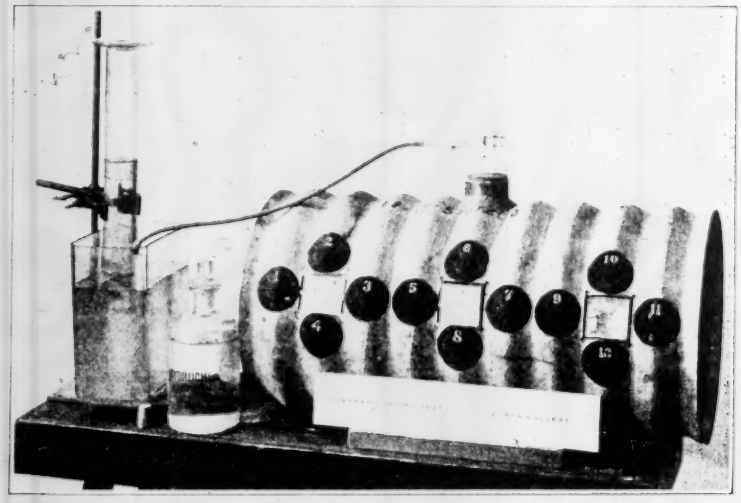


FIG. 3.—Showing Apparatus in Position on a Corrugated Culvert Section.

"Four Cushman spots were made in circular form upon three corrugation ridges and a regular test run upon a $2\frac{1}{4}$-in. square sample taken in the central portion between the four spots. It will be noted how closely this checks with the average of the figures from the four Cushman spots.

FACTORS.

"Weight of coating on each Cushman spot was determined by the following formula:

$$H \text{ (in cc.)} \times 0.00272 \times \frac{5.08}{\text{area}} \text{ (sq. in.)} = \text{ounces per sq. ft. actual surface.}$$

The factor was determined

$$\frac{\text{oz. per sq. ft.}}{\text{H (in cc.)}} \text{ which is the same as } \frac{0.00272 \times 5.08}{\text{Area (sq. in.)}} = \frac{0.0138176}{\text{Area(sq. in.)}}$$

"The average in all cases are averages from all tests and not the average of the maximum and minimum. The factors are as follows:

	Minimum.	Maximum.	Average.	Greatest Variation.
Flat Sheet.....	0.00258	0.00266	0.00262	0.00008
Corrugated Sheet...	0.00246	0.00251	0.00249	0.00005
12-in. Culvert.....	0.00247	0.00250	0.00247	0.00003

By multiplying the greatest difference of factors (0.00266 − 0.00246 = 0.00020) by 600 cc., a difference of 0.02 oz. per sq. ft. is obtained.

From this it will be seen that even should the same factor be adopted for all kinds of tests, the greatest variation would not be over 5 per cent."

From all tests conducted, the writer concludes that the apparatus as now constructed[1] and run will give results accurate to within 0.05 oz. per sq. ft., and that for ordinary work only two factors will be needed: a factor for flat sheets, and a factor for corrugated sheets and 12-in. culverts or larger. For more exact work, factors for each size culvert can be determined. It is believed that this apparatus will prove to be a great time-saving device in the determination of coatings on galvanized culverts.

The author is much indebted to Dr. G. W. Coggeshall, Mr. J. A. Aupperle, and Mr. H. E. Brooks for aid in developing this test.

[1] The apparatus as now constructed is furnished with a three-way glass stop-cock at *H* (Fig. 2). This stop-cock has two tubes, one of which is flush with the bottoms of the stopper *E* and the other which takes the place of delivery tube *G* in Fig. 1, reaches almost to the bottom of the cell *A*. This obviates having to slide *G* up and down as described. The portable apparatus with a calibrated burette and rings is put up in a convenient carrying case.

DISCUSSION.

Mr. Burgess.

MR. G. K. BURGESS.—I should like to express my appreciation of this test, which strikes me as a most excellent one. As Mr. Cushman said, at his suggestion we constructed and tried out in the laboratories of the Bureau of Standards his original type, which has a larger volume and is entirely of glass; and we ran, of course, into some of the difficulties of which he spoke, due to the uncertainties of temperature variation. However, even with the considerable variation present in the case of sheets with which we worked, the results are fairly comparable with other tests which can be made. Undoubtedly this modification of a smaller volume is a great improvement and it is evidently particularly adapted, not only for laboratory work but also for field work. I do not think it would be advisable to quote our actual figures on the subject; they are of the same range Mr. Cushman has noted and represent properly only the preliminary stage of development of the apparatus.

Mr. Aupperle.

MR. JAMES A. AUPPERLE.—Several years ago I developed the hydrochloric acid - antimony chloride method which Mr. Cushman describes in his paper. This method necessitated cutting a sample to a definite size, weighing it carefully, immersing it in the hydrochloric-acid solution until the spelter coating had dissolved, washing, scrubbing, drying and reweighing. Cutting the sample to a definite size could be eliminated, provided one had at hand a planimeter by which the area could be determined.

The hydrochloric acid - antimony chloride method was found to be very accurate. Committee A-5 on Corrosion of Iron and Steel made an exhaustive test of this method and the lead-acetate method which was in general use. In 1917, the committee reported that the method was quite accurate and recommended its use.

Mr. Cushman has now made a very radical improvement in the method which does not necessitate cutting the sample, and, therefore, the original section is not damaged, as the spot where the coating has been determined can be recoated either with paint, or with metal by the use of a blowtorch. The fact

that this method can be used in the field will be appreciated by engineers and chemists, as the material can be analyzed at the project or in the factory and delays are not occasioned on account of waiting for the laboratory results before accepting the material. Mr. Aupperle.

I have seen a man cut a sample from a culvert with a hack-saw, and then send it 600 miles to be flattened out and cut to size. The laboratory to which the sample was sent did not have means for flattening or cutting, and, therefore, had to send it to a machine shop, from which it was finally returned to the laboratory for analysis. This procedure consumes a large amount of time and is very unsatisfactory. Mr. Cushman's method will obviate such inconvenience, as the material can be accepted or rejected within a very short time by the engineer making his own tests.

MR. J. ASTON.—About ten years ago I was identified with some investigations of zinc-coated sheets, and the hydrogen-evolution method was then used in connection with that work. While the tests were not conducted nor was the equipment on the elaborate scale Mr. Cushman has developed, and while the general purpose of the tests was not quite the same, still the results confirmed all that Mr. Cushman has said with regard to the value and simplicity of this method of testing for zinc coatings. The fundamental fact that it is a volumetric method is in itself an important advantage. Mr. Aston.

I rose particularly because, in connection with our work, there were some interesting sidelights on the rate of hydrogen evolution with the different kinds of coating. In our tests, the rate of solution was very much slowed down as compared with what Mr. Cushman has shown us here: that is, the time extended over a period of from 15 to 60 minutes for the total solution. The rate of hydrogen evolution was observed at intervals of every couple of minutes. Also, in connection with the apparatus a normal half cell was connected up so that single potentials of the coatings could be noted and coupled with the rate of hydrogen evolution. There were some very interesting curves representing the rate of solution of the different coatings; hot galvanized, sherardized, and electro-galvanized.

If the single potential in volts is plotted against the time in minutes while solution is progressing, the hydrogen evolution

Mr. Aston. curve will follow the general configuration of the potential diagram (Fig. 1). The electro-galvanized coat started in at about 0.5 volt, and continued at this value in almost a straight line for 30 minutes, then dropping off rapidly to zero. The amount of coating was approximately 0.6 oz. per sq. ft.

The hot galvanized coat started in at about 0.5 volt, dropping off rapidly in about 15 minutes, with a slight jog at 0.25 volt. The total time of solution was between 15 and 20 minutes, while the weight of coating was slightly over 1 oz. per sq. ft.

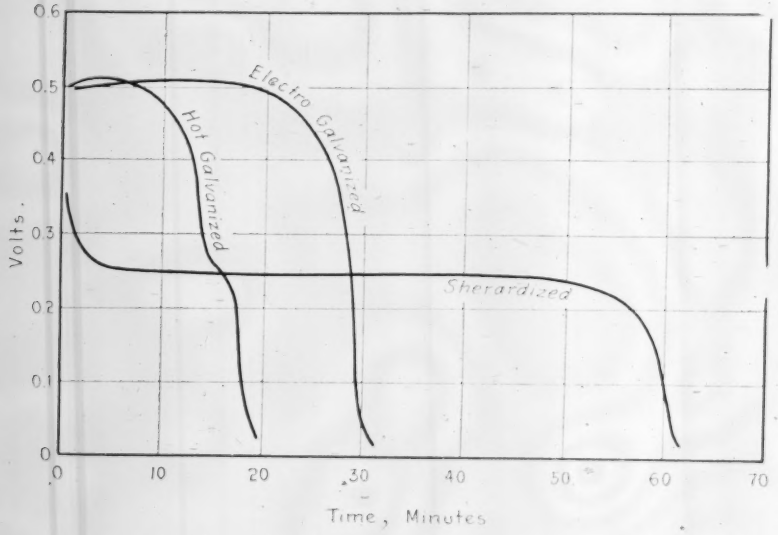


FIG. 1.—Potential Diagram.

With the sherardized coating, while the initial voltage was somewhat higher, the curve follows a practically straight line at a value of 0.25 volt, throughout the entire time of solution of 60 minutes. The weight of coating was 1 oz. per sq. ft.

An interesting feature is the rapidity of solution of the relatively heavy hot-galvanized coating (15 to 20 minutes) as compared with 30 minutes for a lighter weight electro-galvanized coating, and 60 minutes for about the same weight of sherardized coating. Another interesting feature is the slight jog at 0.25 volt for hot galvanizing, and a continued voltage at this value

for sherardizing, indicating the intermediate zinc-iron bonding alloy in the former case, and a practically entire coating of this alloy in the case of sherardizing. Electro-galvanizing shows no jog, being made up of zinc only, with absence of intermediate alloy. Mr. Aston.

MR. G. E. THACKRAY.—I should like to ask Mr. Cushman if it is natural to suppose that some portions of the zinc would disappear before other portions, leaving the acid to work at the same time upon the exposed steel with slight evolution of hydrogen gas from the bare portions of the steel which gas would be added to the other gas and thus give a higher indication. Mr. Thackray.

MR. ALLERTON S. CUSHMAN.—We have never seen the slightest indication of such an effect. I think that the method is accurate, but it should be remembered that no two spots on any galvanized sheet check each other exactly because there is a greater variation in the weight of coating between spot and spot than there is variation in error of the method. Mr. Cushman.

MR. A. N. FINN.—I should like to call attention to one advantage in this method as it appealed to me particularly, and that is the possibility of determining the quantity of zinc on one side only of the sheet. During the war, at the Bureau of Standards, we had occasion to examine a great many pieces of zinc-coated material, and in order to evaluate the coating, particularly electroplated coatings on hollow pieces, such as closing caps, boosters, adapters, and similar material, we had to first cut the specimen and then weigh it, coat one side with wax, strip off the zinc from the other side, remove the wax, and then strip the clean side and weigh it, which made it very laborious. This new method enables one to find the amount of zinc on one side only, which gives the value of the coating. We found that the weight of coating determined by the antimony-hydrochloric acid method was quite variable, that is, quantity of zinc on opposite sides of the sheet did not have any relation to each other. Mr. Finn.

AN INSTRUMENT FOR MEASURING THE HIDING POWER OF PAINTS.

By R. L. Hallett.

The hiding power of a paint, or its ability to conceal the surface over which it is applied, is an important consideration. Much attention has been given to the question of hiding power, and many references to it are found in the literature, both scientific and otherwise.

A number of instruments have been devised for measuring the opacity or hiding power of paints. One instrument was described by Mr. G. W. Thompson in a paper presented before the American Institute of Chemical Engineers at their annual meeting held in December, 1912. This instrument was called an Opacimeter, and it was designed to measure the opacity of paints in the liquid form by measuring the light transmitted through various paint thicknesses. Another instrument called a Cryptometer was described by Dr. A. H. Pfund.[1] This instrument also measures the paint in liquid form, but instead of measuring transmitted light, it determines the thickness of liquid paint necessary to completely hide the surface on which it is placed. Mr. S. E. Sheppard[2] described a Turbidimeter, which determines how well a liquid paint will hide a grating submerged in it.

All three of these instruments measure the opacity or hiding power of the paint in its liquid form. They are very useful but are not adapted to the measurement of a dry and matured paint film. Paint is a practical material used for beautifying and protecting surfaces on which it is applied, and it invariably dries to a hard paint film. The hiding power of a paint is one of the important considerations, because one of the things required of a paint is that it shall conceal the surface on which it is applied. As the hard dry film is the condition finally

[1] *The Journal of the Franklin Institute*, November, 1919.
[2] *The Journal of Industrial and Engineering Chemistry*, February, 1920.

reached by the paint, a measurement of hiding power, to have the most practical value, should be made on the dry paint film.

Measurements that are made on paint in the liquid form do not take into consideration the practical spreading rate. All liquid paints are made to brushing consistency so that they may be readily and properly applied with a brush. Paints are made of so many different materials used in so many different proportions that their working qualities under the brush vary greatly, and paints which appear to have the same consistency may have quite different practical spreading rates, for when the paint is applied it must be put on in a workmanlike manner, no matter what spreading rate results. It is, therefore, evident that there are two things to be considered in measuring hiding power: one is the opacity or hiding power of the paint itself, and the other is the practical spreading rate. A measure of hiding power should be made on the paint after it has been spread at the practical spreading rate and has become dry and matured. The practical spreading rate should be determined by actual application on a large surface.

We have recently developed an instrument which does measure the hiding power of a paint after it has been spread in a thin film and allowed to dry. The instrument is shown in Fig. 1, and consists of a regular microscope frame with a long tube fitted with a plain ground-glass objective, and having simply a small circular opening for the ocular. The principles involved are not new, but the application seems to be novel, as we do not know of these principles having been previously used for this purpose. If a piece of ground glass, or other more or less transparent material which has the property of highly diffusing or dispersing the rays of light which pass through it, be placed in direct contact with a surface having two colors or two shades of the same color, and if the surface be viewed through the glass, the two colored portions and the line between them will be perfectly clear and distinct. We have found that as the ground glass is withdrawn from the surface, the line between the colored portions immediately becomes blurred and indistinct, and the colored portions themselves also become blurred and tend to blend into each other. This effect is increased as the ground glass is further withdrawn until a point

is reached where the entire field becomes blurred and blended, so that it appears to be of uniform color, and there is no distinction between the two colored portions.

We have also found that if one of the colors be partially obscured, as by having applied over it a semi-opaque coat of a paint of the other color, and the contact and withdrawal of the

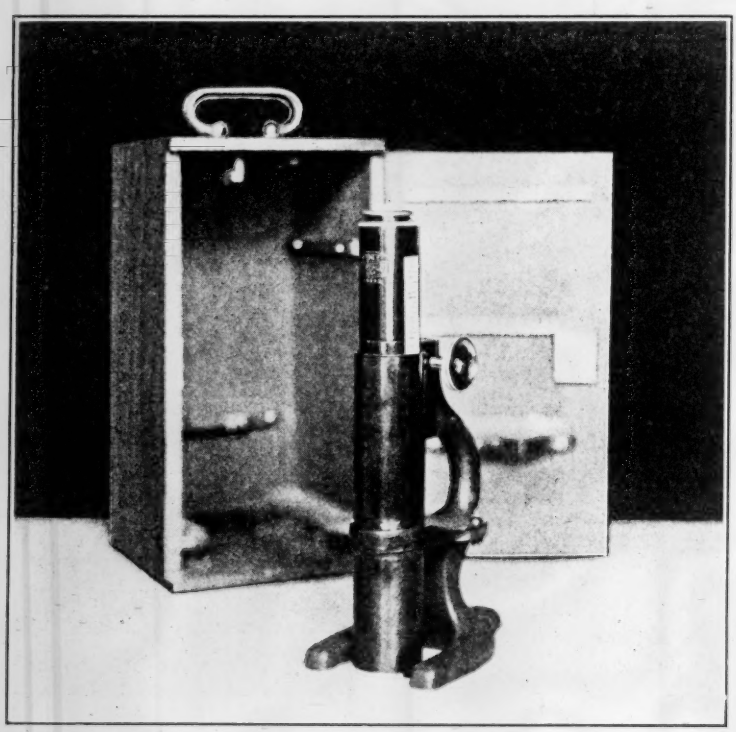


FIG. 1.—Instrument for Measuring the Hiding Power of Paints.

ground glass be repeated, the two colored portions of the field will blend and the field will appear to become uniform when the ground glass is withdrawn to a much shorter distance from the surface than was the case where the full original colors were used. The application of the coat of paint over the surface partially hides the portion of the surface which is not the same color as the paint, and the degree of hiding may be measured by the distance

through which the ground glass must be withdrawn to blend the field. The portion of the surface which has the same color as the paint of course remains unchanged in color and offers the same basis for comparison. The decrease in sharpness of the image and the blending of the field, as the ground glass is withdrawn, is due to the diffusion of the light. The colored surfaces diffuse the light equally in all directions, but when the ground glass is in contact with the surface, the diffusion takes place above the glass and the eye sees the two colored portions distinctly. As the ground glass is removed further and further from the surface, the diffused rays from the two colored portions of the surface spread in all directions so that the rays from each color tend to mingle with those from the other color and strike the ground glass mixed together. This results in a gradual blending of the two colors over the entire field. The ground glass finally reaches a point where the field seems to become blended into one uniform color. As the blending is dependent on the diffusion of the rays, it must be proportional to the square of the distance between the ground glass and the surface viewed, as diffusion varies directly with the square of the distance. Theoretically, there would never be a perfect blend, as each part of the field would always transmit to the eye more rays of its original color than of the color of the adjacent part whose rays are diffused on to it. It is, therefore, apparent that the theoretical distance at which the field would become perfectly blended, would be infinity.

Fechner's Law[1] states that "the least perceptible difference in brightness measured as a fraction of the whole is approximately independent of intensity, extremes excepted, and independent of wave length, extremes again excepted." Konig and Brodhun[2] have shown that the least difference in brightness which is perceptible to the eye is from one to two per cent, and while the field of this instrument should theoretically be perfectly blended only at infinity, the application of Fechner's Law shows that when the difference between the two parts of the field has been reduced to from one to two per cent, the parts appear to be perfectly blended, and it is, therefore, possible to obtain practical end point readings within the limits of the instrument.

[1] P. G. Nutting, "Outlines of Applied Optics," p. 120 (1912).
[2] P. G. Nutting, *loc. cit.*, p. 126.

Fechner's Law shows that the readings are independent of the intensity of the illumination because the eye tends automatically to regulate itself to any degree of illumination, extremes excepted.

In order to standardize the instrument in terms of exact mathematical proportion of hiding power for each position of the ground glass, a large number of points were determined. A black and a white paint were used, each being the best obtainable color. Disks of cardboard were painted with the black and the white, and a large number of grays were prepared by mixing the black and white together. These grays were so made as to give a series ranging from the black to the white. Disks were also painted with each of the grays. All of the disks were then analyzed for black and white on the Howland Color Photometer which gave the percentage of white in each of the grays, and, therefore, gave the hiding power represented by taking the black and applying over it a thin coat of white which would produce the same gray. Fields for observation were made up by using the white and each of the grays in turn, one disk simply being lapped over the other. These fields were measured with the instrument, thus establishing for a large number of distances the mathematical proportion or percentage of hiding power represented when the ground glass was at that particular point. From these points a curve was plotted, both on square and on semi-logarithmic plotting paper, using the distance as one coordinate and the percentage of hiding as the other. On the semi-logarithmic paper, with the distance plotted to the logarithmic scale and the percentage of hiding to the usual scale, the curve proved to be a straight line, which determined its character and provided a method for correcting the minor experimental errors in the curve on the square paper. These errors were found to be very small, showing that the standardization was quite accurate, but the curve finally adopted for converting readings is the one on square paper corrected from the semi-logarithmic straight line. Fig. 2 shows the standard curve used for converting readings of distance into hiding.

As shown in Fig. 1, the instrument has regular microscope adjustments for raising the tube and has a fixed shell around the tube extending clear down to the under side of the base. In its bottom position the ground glass is in contact with the surface

on which the instrument stands, so that the instrument may be placed on any surface which is to be measured. The surface may be of any size and shape. There is a small, narrow slot in the bottom of the outer tube through which the illuminating rays are thrown. This insures uniform illumination at all positions of the tube. The moving tube is fitted with a scale which records, in millimeters, the position of the ground glass. The end point obtained with any field is fairly sharp, and the

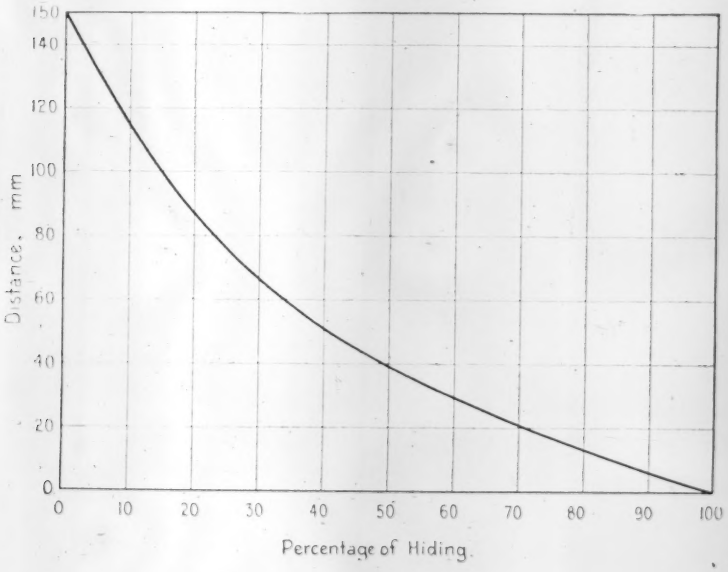


FIG. 2.—Calibration Curve.

sensitiveness of the readings seems to be within five per cent of total hiding.

For a practical measurement of hiding power, a white panel, on which is painted a broad black stripe, is given one coat of the paint which is to be measured. The panel is painted at the spreading rate previously determined by practical test. A measure of the hiding of the black line gives the hiding power of the paint under the standard test conditions. By similar tests with other paints, comparisons between different paints may be obtained. Fig. 3 shows four views of the same field taken at

FIG. 3.—Photographs taken through the instrument, showing four views of the same field with the ground glass at different positions. The views range from almost complete contact with the surface to almost complete blending of the field at the end point.

different positions of the ground glass, ranging from almost complete contact with the surface to almost complete blending of the field near the end point.

The hiding power of pigments may be determined by making various pigments into paint, using the same volume of each pigment and the same volume and kind of vehicle. White panels with a black line may then be painted, using the same spreading rate in all cases. As the same volume of pigment and vehicle is applied to a unit surface in each test, a measure of the hiding power of the dry paint films will show the relative hiding power of the various pigments when mixed with the vehicle used in the tests. In this case the tests will not be practical measures of paint hiding power, as the paints are spread at the same definite spreading rate, which might be impossible if practical conditions were considered. Measurements made by this test apply, of course, only to the hiding of the black line on a wh te background and might be quite different if the line or background were of another color.

Work done along this line, using linseed oil as the vehicle, shows the following relative hiding powers for the white pigments, on the volume basis:

PIGMENT.	HIDING POWER.
White Lead	100
Basic Lead Sulfate	82
Titanox B XX	167
Zinc Oxide	103
Lithopone	85
Barytes	1
Whiting	5
Asbestine	2
China Clay	4
Gypsum	1

White lead was taken as the standard and arbitrarily given a hiding power of 100.

It is not necessary that the field be composed of white and black or white and gray, as a paint of any color may have its hiding power measured in the manner described. Color, tint, and tone do not influence the instrument, but may greatly affect the hiding power of the paint. Some colors will hide the

standard black line much more readily than will others. Carrying the idea still further, the background of the panel, and also the stripe, may be of any color, so that the methods of working may be greatly varied, and many kinds of practical tests for hiding power may be carried out within the limits of accuracy which the instrument possesses. Aside from standard tests over prepared striped panels, this instrument may be used for testing the hiding power of almost any paint work.

As the instrument can be moved about and used on different parts of a painted surface, variations in hiding such as over knots and dark spots in lumber may be determined. The hiding power of a paint, which has been applied over a surface of uniform color having no darker portions to contrast with lighter portions, but which does not completely hide the surface under it, may also be measured. Such a paint has a uniform hiding power, but less than one hundred per cent. Such work would be typical of much of the practical painting work on buildings and other objects, and the measuring of the hiding power of such paint is perhaps the most practical application of this instrument. The hiding power of any paint under these conditions may be found by painting a small card with the paint used for the finishing coat. Enough coats of the finishing paint should be used to hide the card completely. If the finishing coat on the building does not completely hide the surface over which it was applied, a contrast between lighter and darker surfaces may be obtained by laying the card against the finished paint. Readings of the instrument, taken on a field composed of part card surface and part paint surface, will then determine the percentage of hiding which has been obtained in the painting work.

Instead of the single objective observing a single field which must be divided into two parts by the lighter and darker paint portions, it would be possible to use a double field observed through two objectives separated from each other so that through one could be observed the lighter paint portion, and through the other the darker paint portion. These two fields could be brought together by a collector ocular and thrown together, making two halves of a single field for observation. While this arrangement would be possible, our experimental

work would indicate that an instrument with a double objective arranged in this way would not give as sensitive readings because of the difficulty in detecing slight differences between the light and dark parts of the field, and because the decrease in difference between the light and dark parts could be brought about only by the decrease in illumination, as the ground glass was withdrawn from the surface, and not by a diffusion of the colors into each other as is done with the single objective instrument. We believe that the single objective instrument is more useful than the double objective, although perhaps the latter could be developed.

A specially prepared ground glass must be used for the objective of this instrument, as it must give the right amount of transmission and diffusion to just blend the field when the instrument is at the top of its stroke and a full black and white surface is under observation. Such a ground glass is easily prepared by polishing down a glass which is overground until just the right point is reached.

It is often desirable to have a name by which a piece of apparatus may be designated. We have considered various names which might be applied to the instrument we have developed, but there are so many names already in use for instruments of a somewhat similar kind, that we feel it is not desirable to adopt a new name and we prefer to describe it simply as an instrument for measuring the hiding power of paint.

DISCUSSION.

Mr. Hall. MR. C. H. HALL.—It occurs to me that this instrument might be applied to a more practical purpose. There has recently been devised an instrument known as the cryptometer for determining the true opacity of paint. Two pigments showing the same result with the cryptometer instrument may be entirely different when brushed out, owing to the difference in brushing. Mr. Hallett's instrument measures the relative covering values of paints. Now, it is frequently difficult to determine the spreading rate of a paint on small panels used in testing. Would it not be possible to use this instrument in conjunction with the cryptometer to determine the rate at which the paint has been spread on a test panel?

Mr. Hallett. MR. R. L. HALLETT.—To calculate the spreading rate used for any test from the readings of the cryptometer and this new instrument, it is necessary to have a definite mathematical comparison between the two. Such a comparison is required between the thickness of film which hides completely and one which hides only partially. We have thought at times that the hiding power of a paint film was a logarithmic function of the thickness, but we have no right to base calculations on this assumption until we have demonstrated that it is true. The relation between hiding power and thickness is not a simple one. If we double the thickness of a paint film we do not double its hiding power.

Mr. Hall. MR. HALL.—No, but the relation could probably be devised and expressed by some formula.

Mr. Hallett. MR. HALLETT.—If we wish to assume that the hiding power is a logarithmic function of the thickness, we can work out a formula for comparing various thicknesses and the corresponding hiding powers and, therefore, the spreading rates.

We have worked out such a formula and at the present time have under way a series of experiments in which we are measuring paints with the cryptometer to determine the thickness for complete hiding, and also measuring them with this new instrument to determine the thickness for some degree of hiding less than complete. We will then compare the two and.

try to determine whether the logarithmic formula expresses the true relation between the readings. So far we have not been able to demonstrate that the logarithmic formula correctly determines the comparison, and until the correctness of this formula has been demonstrated we have no right to use it. If we do not have some definite mathematical ratio, we have no method of comparing the readings made with the two instruments. **Mr. Hallett.**

MR. H. A. GARDNER.—I think both Mr. Hallett's instrument and the one devised by Mr. Pfund[1] will be of great value to the engineer and chemist for determining the comparative hiding power of two paints or enamels. The most important consideration brought out in both papers, in my opinion, is the effect of a trace of color on the hiding power of a pigment. For instance, a pure French-process zinc oxide, because of its purity and clarity of color, may hide less than an American-process zinc oxide which may contain a very small trace of color, possibly iron oxide. It was shown that just a trace of lampblack or chrome yellow added to a white pigment would increase the hiding power of that pigment to a very great extent, 30 or 40 per cent. This brings out a practical point to the manufacturer making white enamel out of a perfectly pure white pigment. If a trace of carbon black, ultramarine blue, chrome oxide, or a yellow of some kind is added, an enamel with much greater hiding power would be obtained without disturbing the apparent whiteness of the enamel. In the oilcloth industry I think this will have a special application. White enamel is applied to oilcloth. If slightly tinted, the hiding power of the enamel might be increased tremendously. **Mr. Gardner.**

MR. F. P. VEITCH.—I should like to ask what steps have been taken to insure obtaining identical ground glass in different instruments. I can foresee that that is going to make all the difference in the world in the result. **Mr. Veitch.**

MR. HALLETT.—We found that a highly ground glass would blend a full black and white field within an inch or two, and as we desired the full 150-mm. stroke of the instrument, we took an overground glass and polished it with emery and turpentine until the full black and white field was just blended by the full stroke of the instrument. This particular glass and calibration curve apply only to this particular instrument. **Mr. Hallett.**

[1] See p. 440.—ED.

Mr. Hallett. The instrument could be standardized by using a definite length of stroke and definite standard parts with a standard curve, but the ground glass would have to be carefully prepared.

Mr. Pfund. MR. A. H. PFUND.—I should like to say just a word in regard to these two instruments which are contrasted with one another. I think that each one of them has a field of its own. By that I mean, the cryptometer is designed to give the true theoretical hiding power. With an infinitely thick layer of paint, we can hide any background; we want to find the least thickness that will do it. The cryptometer is designed to give us the theoretical value of the hiding. If Mr. Hallett's instrument is capable of yielding measurements when the hiding is complete, it ought to give results in substantial agreement with the cryptometer, so long as the paint in the wet state and in the dry state has essentially the same hiding power. Now I have carried out a number of experiments with ordinary (linseed-oil) paints which almost obliterated a panel of black and white background, and it was found that, as the paint was allowed to dry in the light, the black spots were neither more nor less hidden than they were when the paint was wet, so that paints which do not change their hiding power with drying, ought to yield substantially the same results with the two instruments. On the other hand, if you have a cold-water paint which, when wet, has a small hiding power, and when dry, a large hiding power, then the cryptometer can not be used and Mr. Hallett's instrument comes in to its exclusion, provided, as previously mentioned, that this instrument will yield readings when the hiding is complete.

In regard to the calibration of the instrument presented by Mr. Hallett, I should like to know what ground he has for saying that he has the brightest white and the blackest black. The blackest black has zero brightness, and the brightest white has a brightness depending on the intensity of the light used. How are you going to calibrate and be sure you are using just the right kind of light for the whitest white and the blackest black? If you have a box the inside of which is painted black and put a hole in it, you can illuminate it with the most intense sunlight without affecting the intensity of the light that comes out of the hole; but if you have a piece of white paper alongside of that

you can change the intensity by any amount you please. I should like to know what the calibration of the instrument on this basis is. Mr. Pfund.

MR. HALLETT.—As Mr. Pfund suggests, this instrument may be used for measuring water paint, and it may also be used for paint containing a large amount of volatile thinner. With the cryptometer the paint would be measured with the volatile thinner in it, and with this instrument it would be measured after the evaporation of the volatile thinner. There might be considerable difference in the hiding power between a flat paint which had dried and the same paint in the liquid form containing all of the volatile thinner material. Mr. Hallett.

In calibrating the instrument we did not take the purest black and white obtainable, but the best black and white pigments we could get for use in the laboratory. We analyzed in the Howland Photometer not only the grays but also the black and white. We found that the white contained black, the black contained white and that they both contained red and other colors. The other colors were constant and we considered the white as representing complete hiding and the black as zero hiding with the various grays lying in between, their hiding being dependent on the relative amount of white which they contained.

A NEW COLORIMETER FOR WHITE PIGMENTS AND SOME RESULTS OBTAINED BY ITS USE.

By A. H. Pfund.

Introduction.

It has been remarked by an eminent physicist that a subject may be said to have attained the dignity of an exact science as soon as it is possible to assign numbers to the various quantities involved, and to establish numerical relations between them. If this criterion be applied to the present mode of determining the color characteristics of so-called white paints, we find that we are not dealing with an exact science. White paints are graded by comparing them with standard (arbitrary) samples. If the paints are too pink, too yellow, too blue or too dark, they are rejected; however, if they fall within the limits of tolerance, they are accepted. To put this subject on a rigorous, quantitative basis it is necessary to devise methods which will tell us whether or not a surface is white. In case it departs from white, we must know quantitatively how great this departure is. To be sure, numerous attempts have been made to apply the methods of monochromatic and trichromatic colorimetry. However, these attempts have been unsuccessful because of the fact that the departure from white is usually so very slight that accurate measurements of this departure are out of the question. In the instrument to be described, the departure is greatly accentuated and is thus made amenable to accurate measurement.

Before taking up a description of the apparatus, it may not be out of place to discuss the term "white." According to Nutting:[1] "White is difficult to define and its definition is more or less arbitrary. Subjectively, white is that color in comparison with which any other color appears tinted. Objectively, the light of the midday sun (blue sky-light excluded), reflected from a non-selective surface, is white. White can be defined in physical units only through its spectral energy curve."

[1] Nutting, "Outlines of Applied Optics," p. 154, Blackstone.

In speaking of a surface as yellow or blue, it is tacitly assumed that white light is incident on the surface. If, therefore, a body reflects selectively, it is to be called "tinted"; whereas, if it reflects non-selectively, it is to be called "white." According to this nomenclature, true grays are whites of different brightness. It is therefore entirely proper to speak of one surface as being "brighter" than another or "more strongly tinted." The terms "whiter than" may not be used because the two concepts—increase in brightness, and decrease in strength of tint—are involved.

The present discussion deals with surfaces of great brightness and small departure from white. In order to accentuate this departure, the method of multiple reflections was applied. If white light be allowed to fall on a surface that is slightly greenish, it is obvious that the diffusely reflected light will contain an excess of green. If now this light be allowed to fall on a second surface, identical with the first, the light reflected will be, relatively, still richer in green. By allowing, similarly, a third and fourth reflection to take place, it is possible to accentuate the green tint very pronouncedly. If a surface be truly white, that is, non-selective, multiple reflections will affect only the intensity of the light, not its spectral distribution. As will be shown later, we have here an extremely sensitive test of selectivity. Anticipating the results to be presented, it may be stated that of the many surfaces studied (papers, salt, sugar, zinc oxide, white lead, precipitated salts, etc.) not a single one has been found that does not depart noticeably from white.

THEORY.

The degree of accentuation due to multiple reflections may be calculated with readiness by studying the change in brightness (coefficient of diffuse reflection) resultant upon the successive introduction of two different gray surfaces into the colorimeter.

Let

I_0 = intensity of incident light,

I_1 = intensity of light after n reflections from material No. 1,

I_2 = intensity of light after n reflections from material No. 2,
B_1 = Brightness or coefficient of diffuse reflection of material No. 1 (known),
B_2 = Brightness or coefficient of diffuse reflection of material No. 2 (known),
n = number of reflections, and
K = instrumental constant,

then:

$$\frac{I_1}{I_2} = \frac{I_0 K B_1^n}{I_0 K B_2^n} \text{ or } \frac{I_1}{I_2} = \left(\frac{B_1}{B_2}\right)^n$$

whence

$$n = \frac{\log \frac{I_1}{I_2}}{\log \frac{B_1}{B_2}}$$

For a substance of unknown brightness B_3 :

$$B_3 = B_1 \sqrt[n]{\frac{I_3}{I_1}}$$

Now B_1 and B_2 may be determined by means of an absolute reflectometer or by means of the usual methods of photometry, in which case use is made of a surface smoked with magnesium oxide, whose reflecting power has been determined (87 per cent) and which serves as a standard of brightness. The intensities I_1 and I_2 are determined with the new colorimeter. The value of n is determined by the relative sizes of the colorimeter plates and of their separation. For separations of the order of the diameter of the upper disk, $n = 3$ or slightly greater; as the separation decreases, n becomes larger. For the actual tests here recorded, the separation was such as to yield the value $n = 3.6$, while in a series of tests later on with a smaller separation $n = 4.2$. If we were dealing with specular reflection, n would necessarily have to be a whole number. However, we are dealing with diffuse reflection and, while n must equal at least 3, it may be considerably larger due to the numerous reflections which take place. Since the human eye cannot detect differences

in intensity less than 1 to 2 per cent (Fechner's law) it is clear that the method of multiple reflections makes possible a discrimination between two surfaces whose brightness difference is, roughly, one-fourth of the above.

EXPERIMENTAL.

The apparatus as actually constructed is shown in Fig. 1. Here L is a 100-watt Mazda C lamp which illuminates the outer

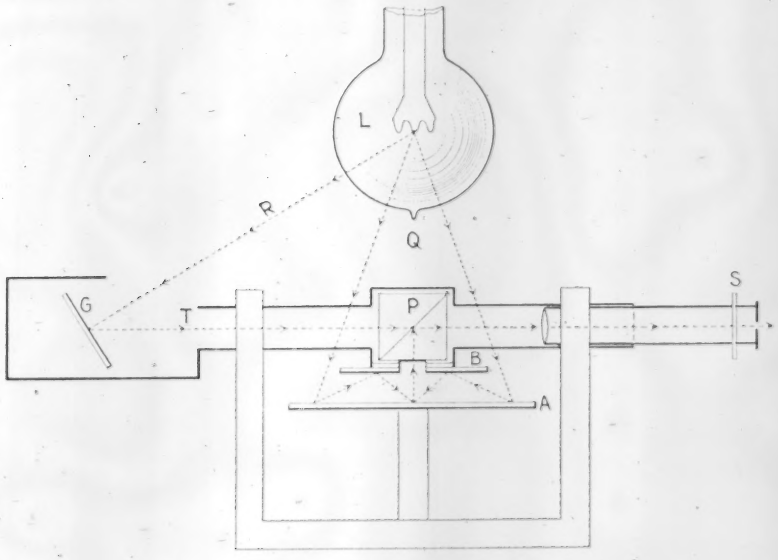


Fig. 1.—Diagrammatic Representation of New Colorimeter.

portion of the circular disk A whose upper surface is covered with the material to be studied. The light, diffusely reflected, illuminates the lower (coated) surface of the disk B which, in turn, illuminates the central portion of the disk A. The light, after multiple reflections, passes upward through a central opening in B and is reflected horizontally by means of the photometer cube P. Another beam of light leaving L is reflected from a disk of clear optical glass G, roughly ground on both sides. (Without going into details it may be stated that the most painstaking tests have shown that such a plate reflects visible radia-

tions non-selectively.) This light passes through the tube T and fills the upper half of the field of view of the photometer cube which has a horizontal line of demarcation and which is viewed through a simple eye-piece yielding a linear magnification of 2.5. The intensity of this beam is varied by rotating the disk G about a horizontal axis. A pointer, attached to the rod bearing disk G, moves over a graduated scale which has been calibrated in terms of light intensities. The intensity of the light leaving G may be varied over a range, the extremes of which are in the proportion of 15 to 1. Whenever it becomes necessary to extend this range in either direction, a wire gauze or rotating sector is introduced at either R or Q. Since the percentage transmission of the gauze or sector may be regulated it is possible to take care of all possible cases.

While this colorimeter lends itself admirably to the methods of monochromatic colorimetry, this method has not been used because it demands a standard source of white light and a highly trained observer. At the present time no such standard source of light has been agreed upon. It therefore seemed advisable to determine the color characteristics simply in terms of the brightness for blue, green, and red light. Accordingly, color screens of dominant hue 460 $\mu\mu$ (blue), 550 $\mu\mu$ (green), and 625 $\mu\mu$ (red) were successively placed in the eye-piece tube at S and photometric balances were established. The readings thus obtained led eventually to a numerical value of the brightness for the above colors of known wave length. These numbers establish the color characteristics of the paint uniquely; standard samples may therefore be discarded.

A discussion of the question whether the ideal paint shall be truly white or yellowish or bluish lies beyond the scope of this paper. Suffice it to say that, if the ideal paint has been realized, it will be possible to define its color characteristics and limits of tolerance in terms of definite physical quantities. Some practical results obtained with well-known paint pigments are to be presented shortly.

In order to avoid discoloration due to the yellowish tint of linseed oil, glycerin was chosen as a vehicle and fairly thick paint pastes were prepared and applied to the colorimeter plates. (The brightness of paints prepared with glycerin are

very nearly the same as that of paints prepared with linseed oil.) The results obtained are shown in Fig. 2. The first point to be noted is that not one of these paints is truly white; for if it were, then the value of the brightness for red, green and blue would be the same and the color curve would be a straight, horizontal line. As a matter of fact, practically all paints are yellowish. A detailed study of the so-called tint limits

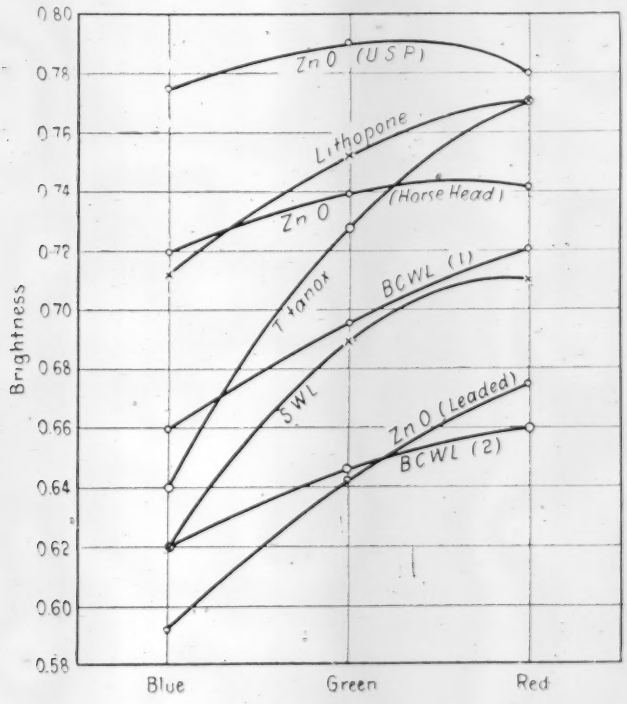


FIG. 2.—Color Characteristics of Standard Paint Pigments in Glycerin

has shown that such pigments, *when compared with one another*, are pinkish, bluish, etc., but in reality, they are all deficient in blue and hence are yellowish. It is needless to comment on these curves as the results speak for themselves. It may be noted, however, that the brightness differences displayed by these pigments, when viewed in daylight, are very closely in the same proportion as the green brightness shown in the curves.

Another problem amenable to test is the yellowing and bleaching of paints. A paint containing only zinc oxide and linseed oil was applied to the colorimeter plates and color measurements were taken daily for a period of two weeks. In this time the paint had yellowed visibly. It was then bleached in sunlight for 15 hours until no further changes were produced. The results are shown in Fig. 3, the dotted curve applying to the bleached paint. It is clear that, while the bleaching helps the

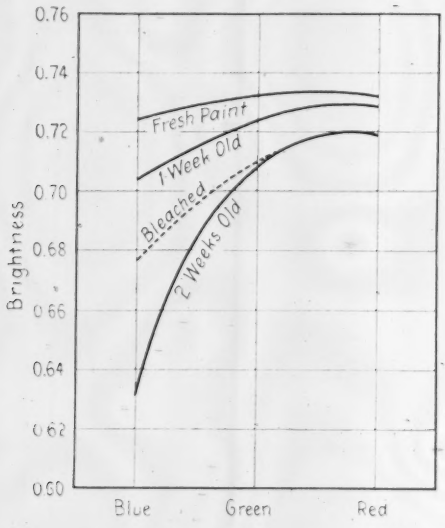


FIG. 3.—Color Changes of Zinc Oxide in Linseed Oil.

"color," the paint never again reaches the brightness and close approach to whiteness which it had while fresh.

Probably the two most important optical properties of a paint are brightness and hiding power. It seemed of interest to investigate a possible relation between these two quantities. The brightness was measured by means of the colorimeter while the hiding power was determined by means of a new instrument, the cryptometer,[1] devised by the writer for yielding numerical values of the true hiding power of a paint (expressed in square feet per gallon). To accomplish the end sought, a considerable

[1] *Journal of the Franklin Institute*, November, 1919.

amount of white pigment was rubbed down to painting consistency with linseed oil. To separate portions of this paint, small amounts of lampblack were added so as to prepare samples of varying brightness. Both hiding power and brightness were determined for each sample. While results are shown for only two paints (ZnO) the same general relations apply to all white pigments (lead, zinc, lithopones, etc.). It is similarly true that

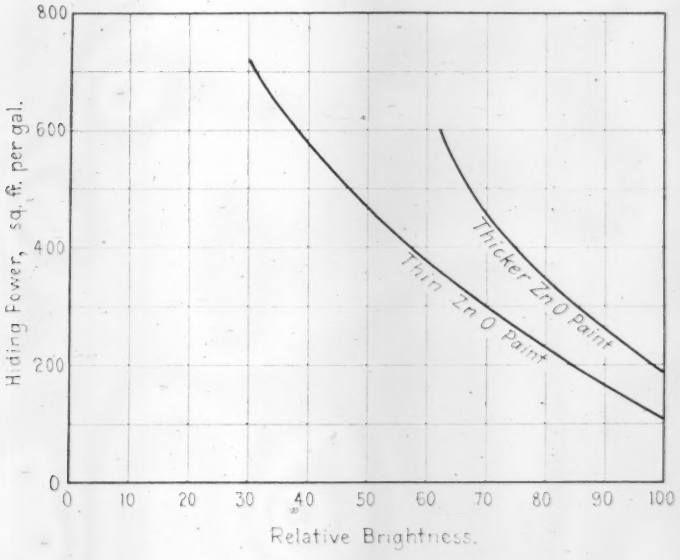


FIG. 4.—Relation between Hiding Power and Brightness of Two Zinc Oxide-Linseed Oil Paints to Which Small Amounts of Lampblack Have Been Added.

the fineness of the lampblack is of comparatively little importance. The results are shown in Fig. 4.

If, from this curve, we calculate the ratio of percentage increase in hiding power to percentage decrease in brightness we obtain an average value of five when the amount of lampblack added to the paint is small. This means that by making a comparatively slight sacrifice in brightness we obtain a relatively large increase in hiding power.

Another interesting consequence of adding lampblack to yellowish paint is the well-known "bleaching effect." While

the lampblack reduces the brightness of all colors, it affects the red and green more than it does the blue. In consequence, the paint takes on a less yellowish tint—in fact, it may be made almost non-selective or even bluish. The effect of such addition of lampblack is shown in Fig. 5.

The test here presented illustrates well the manner in which the new colorimeter and cryptometer yield quantitative data. The absolute values of brightness for the three primary colors are obtained and it is shown that the paint, after the addition of lampblack, has become nearly non-selective. While a decrease

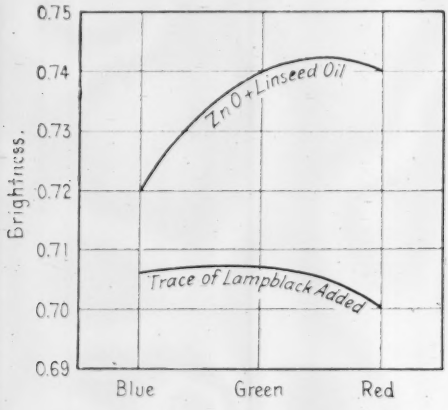


FIG. 5.—Color and Brightness Changes Effected by Addition of a Small Amount of Lampblack to a White Paint.

in brightness of 3.5 per cent has taken place, the hiding power has been increased 17.5 per cent, a result which is altogether worth while since the brightness of the paint has been reduced so slightly that the paint is still to be classified among the "very bright" white paints.

CONCLUSION.

The several concrete examples, cited in this paper, go to show that the new colorimeter is well adapted to solve successfully problems relating to colors of and color changes in surfaces which are nearly white. As a result the entire subject has been advanced from the descriptive to the quantitative stage.

DISCUSSION.

Mr. F. P. Veitch.—I should like to ask Mr. Pfund if he can replace the three pieces of glass he has,—red green and blue. Can he obtain other pieces identical in color? **Mr. Veitch.**

Mr. A. H. Pfund.—That is a very interesting point. In the present instance the pieces of glass I have are of sufficiently large area to supply the scientific world the rest of my lifetime. **Mr. Pfund.**

It is desirable to get these color screens in the form of reproducible and stable inorganic solutions. I use cupro-ammonia to produce a filter for blue light; for green light, potassium bichromate and copper sulfate. For the red, I have no satisfactory solution as yet. I am afraid of aniline dyes. Until I get a satisfactory red solution, I have got to stick to my pieces of glass. The nearest approach was a strong solution of iron sulfo-cyanate, but this was too yellowish. I am glad this point was brought up, for some time someone may accidentally run across such a solution, and if they do, I would appreciate their letting me know about it.

Mr. G. W. Thompson.—The work described by Mr. Pfund is most interesting. I have been so much interested in the use of the Howland photometer that perhaps my thoughts run more along the lines of Howland's particular system, so that the question I want to ask may not really be expressed in the terms in which Mr. Pfund very properly and usually thinks. He thinks of hues as having two qualities, hue characteristic and hue strength. Now, I am wondering to what extent he is able to control the hue strength of the glass that he uses and to determine its hue characteristics. What is the hue strength of his glass and what effect does it have upon the readings of the instrument? **Mr. Thompson.**

Mr. Pfund.—There is probably no subject known to scientific men in which there is more confusion than in the terminology of colorimetry. It is confusion worse confounded, unless we confine ourselves to the terminology used by the two systems of colorimetry, that is, trichromatic and monochromatic colorimetry. Suppose we have a surface of powdered potassium **Mr. Pfund.**

Mr. Pfund. bichromate; if we illuminate that with white light, we shall get a certain color, essentially yellow. If, now, we place alongside of this sample a piece of absolutely white blotting paper, we can duplicate the particular shade of yellow by allowing a certain amount of red light, a certain amount of green and a certain amount of blue to fall upon that surface simultaneously. By regulating the relative intensities of the red, green and blue, we can match the yellow perfectly. This is the trichromatic system.

The other, or monochromatic system, involves sending down white light upon the white paper and superimposing on the white a certain amount of yellow light of definite wave length and intensity. Now the percentage of yellow light which has to be added to the white light gives the so-called "saturation." For instance, if you have a deep yellow, you will probably have to add 50 parts of yellow light to 50 parts of white, and the saturation would be called 50 per cent; so, in terms of monochromatic colorimetry, you have to know the brightness, that is, the total quantity of the light reflected back; the dominant hue, that is, the wave length of this yellow light; and the percentage of yellow light to the total light. The terminology of these two systems is quite generally adopted at the present time, and, as a result, the confusion resulting from the use of other terms is avoided.

As for the colored glasses, their characteristics are defined by their transmission curves as revealed by spectrophotometric analysis. I must confess my inability to answer the question asked in terms of the physical quantities with which I am familiar.

FURTHER DEVELOPMENT OF THE PLASTOMETER AND ITS PRACTICAL APPLICATION TO RESEARCH AND ROUTINE PROBLEMS.[1]

By Henry Green.

The work presented in this paper is a continuation of the original investigation of E. C. Bingham and the author on the Plasticity of Paints.[2]

Introduction.

The use of viscosity determinations for industrial purposes has been limited principally to the testing of vegetable and mineral oils. The reason is a natural one. Oils are true liquids and as such their resistance to flow can be expressed completely by the viscosity coefficient. This is not the case, however, with the vast majority of liquid-like commercial products, which, instead of being true liquids, are suspensions of solids or liquids in a liquid vehicle. Materials of this type are as a rule *plastic* and not viscous, hence attempts to measure their viscosity have invariably met with failure.

The exact manner in which plastic and viscous substances differ from each other has been clearly described by Maxwell in his Theory of Heat. He points out that any stress, no matter how small, if applied to a viscous liquid will cause permanent deformation, but with a soft (or plastic) solid the stress must exceed a certain finite value before a similar condition arises.[3]

Plastic solids differ from liquids, then, only in that there exists for them a certain definite value of the force applied, below which flow (deformation) does not take place.

Many references can be cited where investigators measured what they have defined as the "plasticity" of clays, but in comparatively few of these cases has any attempt been made to measure the *resistance to flow* of plastic compounds.

[1] A contribution from the Research Laboratories of the New Jersey Zinc Co.

[2] E. C. Bingham and Henry Green, "Paint, a Plastic Material and Not a Viscous Liquid; the Measurement of its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

[3] A graphical method representing this difference is given later. This will show clearly that the resistance to flow of a plastic substance is of a two-fold nature and consequently, unlike viscosity, cannot be expressed as a single coefficient. See Fig. 6, *b*.

Bleininger and Ross[1] forced plastic mixtures of clay and water through an orifice and in this manner were able to measure the amount of pressure required to produce flow. The work of Simonis, who used Zettlitz earth and water mixed to plastic consistency, likewise indicated that it was necessary to apply a certain definite pressure before flow commenced. This pressure will be referred to as the "yield value."

By using capillary tubes instead of an orifice, Bingham[2] not only determined the yield value of clay and water suspensions, but advanced further and calculated their mobility (fluidity).[3] His work demonstrated the fact that the measurements, yield value and mobility, completely express the plastic nature of a substance, and so placed for the first time the determination of plasticity on a substantial basis.

The chief interest in the measurement of plasticity has been in regard to clays. Recently the author, in collaboration with Bingham, extended the field to include the heretofore uninvestigated subject of paints. The results of this investigation showed that paint is plastic, and that its consistency depends on its yield value and mobility. For a complete description of the work reference should be made to the original paper.[4]

While clays and paints have been the principal plastic materials studied up to the present time, they should by no means monopolize the attention of investigators. There is a vast territory existing in the industrial sciences which is open for research. It will take into consideration such products as clays, paints and paint pastes, greases of all kinds, lard, butter and butter substitutes, library paste, cements, plastics, soaps, jellies, and lubricants such as oildag and gredag.

[1] A. V. Bleininger and D. W. Ross, "The Flow of Clay Under Pressure," *Transactions*, Am. Ceramic Soc., Vol. XVI, p. 392 (1914).

[2] E. C. Bingham, "An Investigation of the Laws of Plastic Flow," *Scientific Paper No. 278*, U. S. Bureau of Standards. Bingham uses the term "friction constant" instead of yield value.

[3] Mobility and fluidity are analogous terms. Mobility is used when referring to solids and fluidity to liquids. Fluidity is the reciprocal of viscosity. The term "rigidity" has been used to express the reciprocal of mobility. In the opinion of the author this is rather unfortunate, as it is the "yield value" which imparts a rigidity to substances making them solids. This gives the term two entirely different meanings. The method for measuring yield value and mobility is given later.

[4] E. C. Bingham and Henry Green, "Paint, a Plastic Material and Not a Viscous Liquid; the Measurement of its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

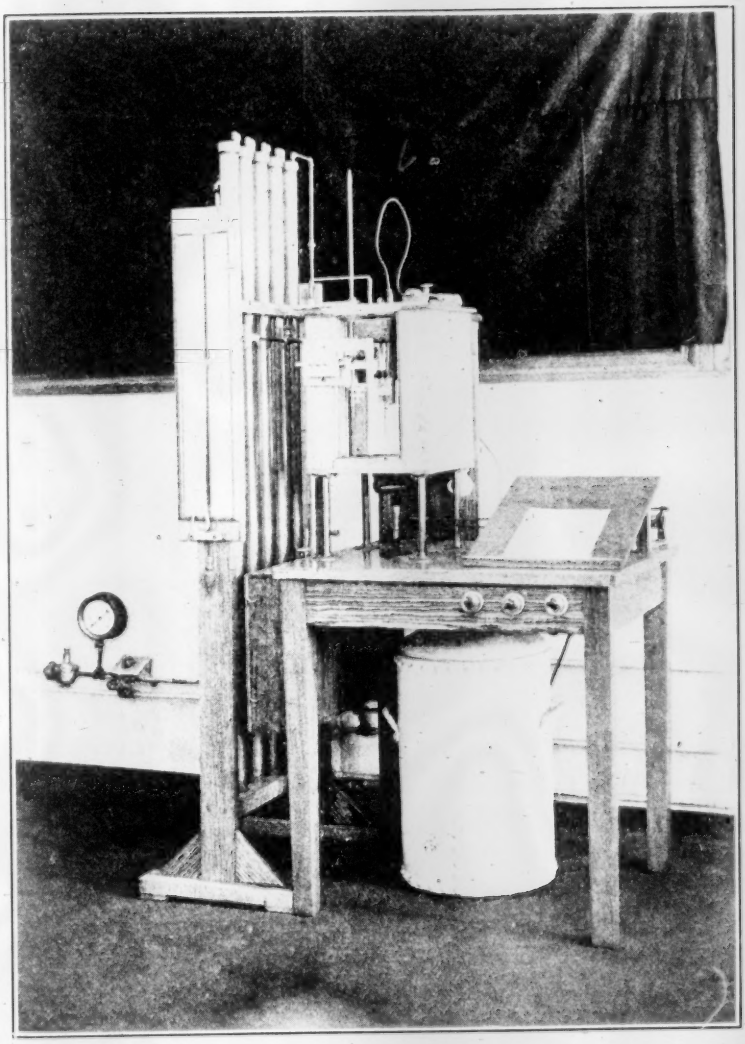


FIG. 1.—The Plastometer with Flowmeter Attached.

THE INSTRUMENT.

The instrument to which the name "plastometer" has been given is a development of the capillary-tube type of viscosimeter. It differs essentially in three respects from the technical instruments in that (1) an externally applied pressure, kept constant and capable of accurate measurement, is employed in place of the varying hydrostatic head of the liquid otherwise used, (2) the ratio of length of tube to diameter is of a higher order of magnitude, and (3) the velocity of flow can be regulated so that the kinetic energy correction becomes negligible.

The principal parts of the plastometer are: a container for holding the material to be tested, into the lower end of which is fastened a capillary; the air pressure system, which includes a stabilizer for maintaining constant pressure; and a flowmeter to measure the rate of flow of the substance as it is forced through the capillary. There are also a water bath, for keeping the container at constant temperature, and a large air reservoir attached to the system.

Only a general description of apparatus will be attempted here as a detailed account is given in the original paper to which reference has already been made. As the flowmeter is a recent addition and as the container has been somewhat altered, a more complete discussion of them will follow.

The Container.—The container is made of brass and should have a capacity of about 20 or 30 cc. It will be seen in referring to Fig. 2 that it is composed of three sections. The top, which is fastened on by means of the screws *C* and *D*, possesses an inlet tube, *A*, and an outlet tube, *B*. Tube *A* is connected with the air pressure and *B* to the flowmeter. The middle part forms the body of the instrument. It has on one side a bore, *E*, which makes tight connections with tube *B*. The bottom part holds the capillary, *F*, and the glass receptacle, *G*. There is also a bore, *H*, making connections with *E*, and two screws, not shown in the drawing, which hold this section in place. Rubber gaskets *I*, *J*, and *K* make the entire system air tight.

Enough of the material to be tested is put in the container until the mark *N* is reached. The distance from the top level of the capillary to *N* is accurately known. In the instrument used in this work it is 4 cm.

The hydrostatic head, which the substance exerts, is found by multiplying its density by the sum of the capillary length plus 4 cm. This is a correction to be added to the main pressure in order to obtain the total force causing flow. It is evident that when the test proceeds the container empties and the hydrostatic-head correction will vary. As the level in the container drops, however, there is a corresponding rise of level in

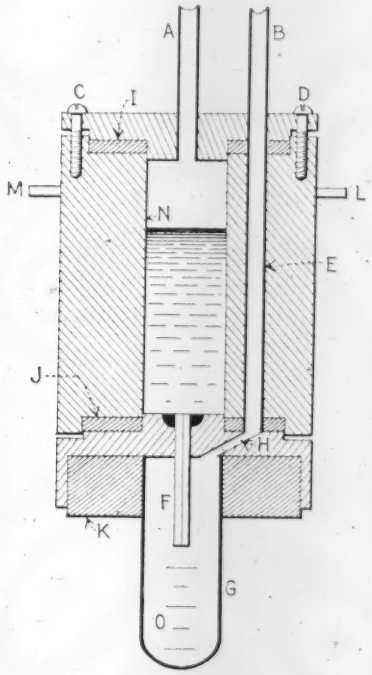


FIG 2.—The Container.

the receptacle, *G*, that can be measured by the scale, *O*. This scale is graduated in such a manner as to give the height of material remaining in the container at any particular time during the test. By this means accurate determinations of the pressure are obtained.

An apparatus of the type described is easily taken apart and cleaned. Suppose paint is the material which has been run: *G* is first removed and emptied. Next, it is rinsed out several

times with small amounts of gasoline and finally with denatured alcohol. A ramrod, covered with linen, is used to remove the last trace of material. The top is then taken off and anything remaining in the container poured out. After unscrewing and removing the lower section, a tightly fitting ramrod is pushed through the body of the container, cleaning it effectively. Suction is now applied to the lower end of the capillary and a few drops of benzol, placed on top, is drawn through. If anything remains adhering to the walls of the tube, it can be dislodged by inserting a fine insulated copper wire.

The Air Pressure.—An air pump in the basement of the laboratory supplied the pressure. As this pressure varied from 20 to 60 lb. per sq. in., it was necessary to place in the piping system a reducing valve which, after regulation, lowered it to 15 lb. and kept it constant to within 2 or 3 lb. A five-pipe water stabilizer which reduces the pressure to the desired amount for making the determination[1] was introduced at some convenient point in the system between the reducing valve and the container. The function of the stabilizer is two-fold: first, it adjusts the pressure to the required value, and second, it maintains it constant to such a degree of efficiency that no fluctuation in the mercury manometer, to which it is attached, is observable even when the meniscus is examined with a lens.

The Manometer.—The manometer tube is bent in the form shown in Fig. 3. A single invar tape, *A*, graduated in centimeters, is suspended back of it, and is held straight by means of a weight, *E*. The entire apparatus is mounted on a mirror, *B*, which should be at least 0.5 cm. thick. The manometer is read by placing a card with a straight edge directly back of the meniscus and between the tape and the mirror. By slight adjustment the edge, *C*, and its reflection, *D*, together with the top of the meniscus, *F*, can be brought into one plane; and to the eye, placed directly in front, the three will appear coincident. Parallax is thus eliminated entirely. If a hand lens is used readings can be checked to within 0.01 cm.

In a plasticity determination the yield value and mobility are obtained (1) from the pressure used, and (2) from the

[1] For a description of the stabilizer and the method of connecting it to the instrument, the original work must be consulted.

rate of flow, caused by that pressure, of the material through the capillary. The rate of flow may be determined by the drop method[1] (if the substance forms drops), but is more easily accomplished by means of a flowmeter, which may be used in all cases except where the material is highly volatile.

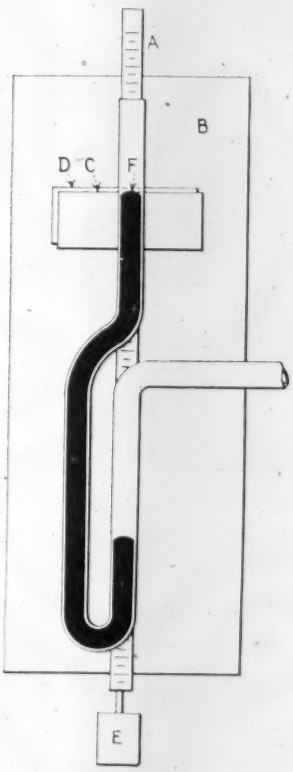


FIG. 3.—The Manometer.

The Flowmeter.—It is evident that during the test, the substance emerging from the lower end of the capillary and falling into the receptacle *G*, Fig. 2, will displace in *G* a volume of air equal to its own volume. If a flowmeter delicate enough

[1] E. C. Bingham and Henry Green, "Paint, a Plastic Material and Not a Viscous Liquid; the Measurement of Its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II (1919).

to measure very small rates of gaseous flow be attached to the side tube, *B*, it will then record the rate of flow of this displaced air, which rate must be identical with that taken by the material itself.

An apparatus capable of measuring exceedingly small rates of gaseous flow can be made by modifying the well-known capillary-tube type of flowmeter in which a pressure is produced, due to the viscous resistance of the gas, that is directly proportional to the rate of flow itself. Fig. 4 shows the flowmeter immersed in a constant temperature bath, *V*, the water level being at *Z*. To the right it is connected to the container by means of tube *B;* to the left, with an air reservoir, made of flasks connected in series and hermetically sealed, the use of which is described further on.

Suppose the stopcock, *T*, to be closed; then as the substance under examination is forced through the capillary *F* into *G*, the air which it displaces from *G* moves up through B, follows the direction indicated by the arrows, passes through the capillary *S*, and from there on through P into the reservoir *X*. In so doing a differential pressure is produced which depresses the meniscus, *Q*, in the manometer *R*. Equilibrium is established in the system as soon as the hydrostatic head in *R* reaches a point where it creates enough pressure to cause the rate of flow through *S* to equal the rate of flow of air coming from *G*.

It is evident that the amount of depression of the meniscus *Q* will be directly proportional to the rate of flow. As this depression is never allowed to exceed 6 mm., it can be measured readily by means of a small comparator attached to the outside of the tank, instead of a cumbersome and expensive cathatometer. If the flowmeter exhausted directly into the atmosphere instead of into the reservoir *X*, slight variations in atmospheric pressure, which are always present, would affect the manometer *R* to such an extent as to make accurate readings impossible. After the determination is finished, the stopcock *W* is opened, preventing an accumulation of pressure in *X*. Next, stopcock *T* is opened. This brings both sides of the manometer rapidly to the same level. Upon closing *W* and then *T*, the instrument is ready for the next reading.

During operation there will be a slight increase of pressure in *X*, which would affect the readings, if allowed to become

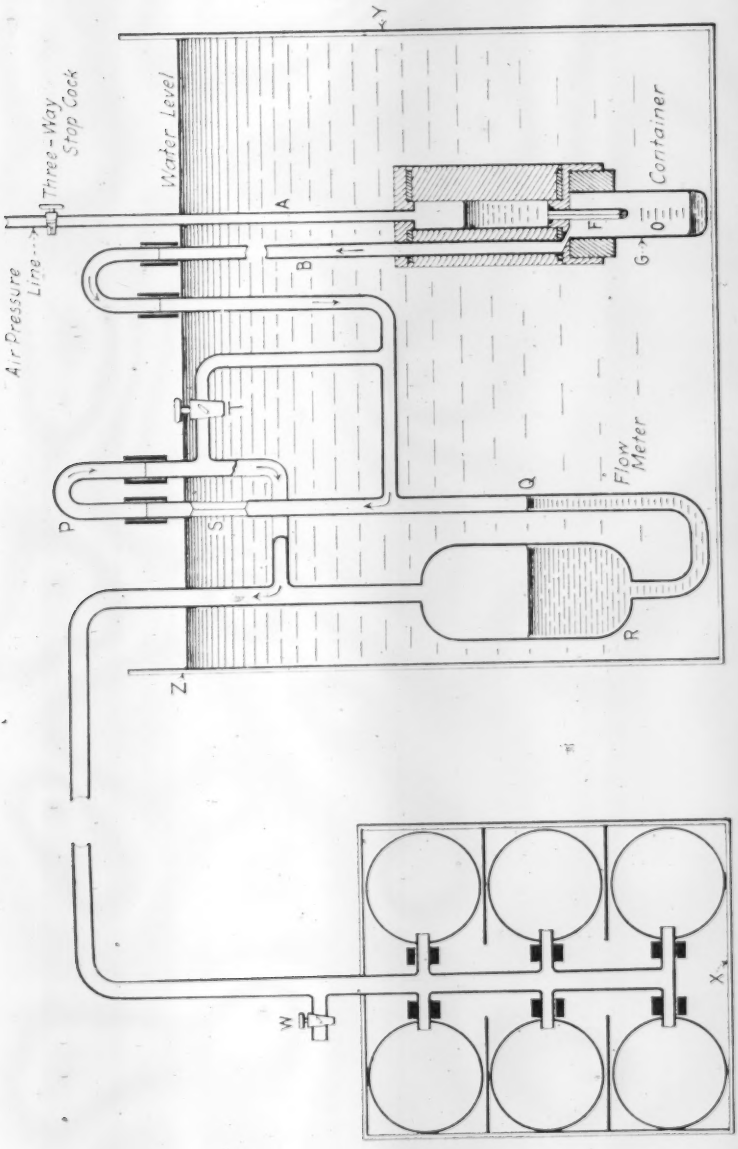


FIG. 4.—Diagrammatic Sketch Showing Method of Connecting Flowmeter to the Container.

appreciable. In order to reduce this pressure to a state of negligibility, the volume of X is made large in comparison with that of the air displaced from G. The reservoir, X, is composed of six one-liter flasks with a total volume of over 6000 c.c.; the amount of air displaced in G is usually never allowed to exceed 0.5 cc. If this ratio is maintained there will be little danger of the "back pressure" becoming troublesome.

The capillary S is approximately 2 cm. in length and 0.03 cm. in diameter. It is not necessary to know its dimensions and the best way to choose it is by trial. A suitable one will

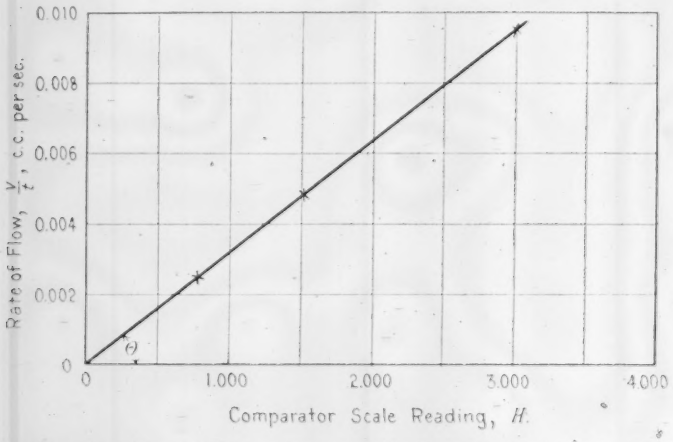


FIG. 5.—Showing the Linear Relationship Existing Between Rate of Flow and the Scale H of the Flowmeter.

cause the manometer to attain a maximum head in 60 to 70 seconds. By removing the arm P, which is fastened on by rubber connections, the capillary may be cleaned by the insertion of a fine wire. At first alcohol was the liquid used in the manometer, but it was rejected on account of the fact that its vapor condensed in S. A light non-volatile mineral oil was found to be more suitable.

The Calibration of the Flowmeter.—In plasticity and viscosity determinations it is necessary to know accurately the radius and length of capillary F. These are obtained by the method of calibration given in the previous work.[1] When they

[1] *Loc. cit.*

are known, the constant of the flowmeter for converting depression of meniscus Q to volume of flow per second, is quite readily obtained, as follows:

The fluidity of some suitable liquid such as a non-volatile oil is first found, the volume of flow being deterimned by means of the drop method. The flowmeter should be temporarily detached. If the capillary F and the pressure are properly chosen the volume of flow per second can be reduced to such a value that the kinetic energy correction becomes negligible. Then from the law of viscous flow through a capillary,

$$\phi = K \frac{V}{t P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and,

$$\frac{V}{t} = \frac{\phi}{K} P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where ϕ = fluidity of the oil, P = the pressure causing flow through the capillary, V/t = the volume of flow per second caused by pressure P, and $K = \frac{8 l}{\pi g r^4}$, where l = the length of the capillary, r = its radius, and g is the gravity constant.

The fluidity having been calculated by use of Eq. 1, the flowmeter is attached and the pressure turned on. For any given value of P the ensuing rate of flow V/t is determined from Eq. 2, ϕ/K being known. Each value of V/t will correspond to a definite lowering of the meniscus Q.

The pressure is now varied, and in this manner a series of rates of flow with their respective manometer readings is produced, which when plotted give a linear relationship so long as turbulence does not take place in S. See Fig. 5. H is the distance in centimeters of the lowering of the meniscus Q.

It is evident that,

$$\frac{V}{t} = H C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where C is the constant of the flowmeter and is equal to $\tan \theta$. The data in Table I are for the flowmeter used in this work.

Method of Using Instrument.—In order to prevent the clogging of the capillary F, all substances that are sufficiently mobile, such as paint, must be passed through a fine screen. With materials of high yield value such as greases and paint pastes, wide capillaries are used, so this operation is unnecessary. Paste, in which skin has formed, should be spread out in a thin layer, with a spatula, on to a glass plate and the objectionable material removed.

Paints and liquids are easily poured into the container; greases and soap jellies should be first melted, if possible, otherwise considerable amounts of air will become included. They should be allowed to solidify before placing in the constant temperature bath. Some practice is required before paint

TABLE I.—CALIBRATION DATA FOR FLOWMETER.

Fluidity of Oil used in Calibration.	Average.	ϕ/K
(1) 4.515 (2) 4.506	4.511	0.00001655

Flowmeter Scale, H.	Pressure, P, g. per sq. cm.	Rate of Flow, $\frac{V}{t}$, cc. per second.	Flowmeter Constant, C.
0.783	152	0.00251	0.003212
1.523	294	0.00487	0.003198
1.524	294	0.00486	0.003188
3.006	581	0.00962	0.003202
Average			0.003200

pastes can be introduced without entrapping air. Small amounts are taken at a time and spread on the inner walls of the container. By jarring they can be made to slide down and so cover the bottom. By this means the container is satisfactorily filled.

After the container is filled it is placed in the thermostat; then connected to the air pressure line and to the flowmeter. It is allowed to come to the proper temperature, and the pressure is turned on and measured. In the course of a minute or so the flowmeter will have attained equilibrium and is read. This reading multiplied by the factor C gives the rate of flow V/t. If the substance under examination is a liquid, this is sufficient data to give its viscosity in c. g. s. units; if it is plastic, another set of readings must be taken at a higher or lower pressure.

For greater degrees of accuracy, as many more readings may be taken as desired.

When the pressures P are plotted against their corresponding rates of flow V/t, the intercept[1] of the curve on the pressure axis is the graphical yield value in grams per square centimeter, and the slope of the curve, multiplied by the capillary constant K, gives the mobility in c. g. s. units.[2] The graphical yield value, which is a function of the capillary as well as of the true yield value, is converted to a value independent of the capillary, by the factor k, the method of determining which is given later.

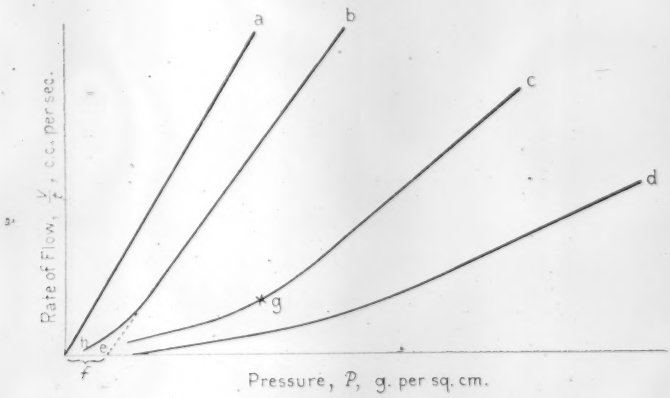


FIG 6.—Various Types of Curves Illustrating Viscous and Plastic Flow.

PRACTICAL APPLICATION OF THE PLASTOMETER.

The Plastic Flow Curve.—The law of viscous flow given in Eq. 1 shows a linear relationship between V/t and P. Furthermore, it indicates that the curve must pass directly through the origin. This is substantiated experimentally when liquids are used, (Fig. 6, *a*). On the other hand, if materials like paint are substituted in place of liquids then experimental results give the relationship shown by the curve *b h*.

The law of plastic flow can be derived mathematically in the same manner as the viscous law, except that a yield value,

[1] Obtained by extrapolating the linear portion of the curve to zero rate of flow. See Fig. 6, *b*.

[2] E. C. Bingham, "The Variable Pressure Method for the Measurement of Viscosity," *Proceedings*, Am. Soc. Test. Mats., Vol. XVIII, Patr II, p. 373 (1918).

f, must be introduced. This law is given in Eq. 4, where μ is the mobility instead of fluidity:

$$\mu = K \frac{V/t}{P - f} \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)^1$$

and by transformation,

$$P = f + \frac{K}{\mu} \frac{V}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

But just as Eq. 1 predicted a linear curve for liquids, so does Eq. 5 indicate the same condition for plastic substances, with the one difference that the former curve passes through the origin while the latter does not. The exact cause of the variance of the experimental results (curve $b\,h$) with the natural or mathematical law (curve $b\,e$) has been a question for argument. It will be shown in the theoretical section of this paper that there exists a peculiar instrumental effect, when substances like paint flow through a capillary, which is sufficient in itself to cause a bending of the curve toward the origin in the region of low pressure. Therefore, it will be assumed, at least until contrary evidence is produced, that if some instrument other than the capillary-tube type of plastometer is used, experimental data will then give the straight line relationship, be.

Paint Pastes.—Until the present, the study of paint pastes has hardly been touched upon. The form of the paste curve, Fig. 6, c, varies considerably from that of paint. The equation of an hyperbole, with its vertex tangent to the pressure axis at the origin, can be used to express empirically curve b. With pastes, however, the vertex has moved to some point, g, and consequently the hyperbole equation, as used for paints, is no longer tenable.

It is evident that only the straight parts of curves b and c are of any value for plasticity determinations. Formerly the asymptote was used to ensure that this part of the curve had been reached. Fortunately for practical purposes, the calculation of the asymptote is not necessary, as a proper selection of capillary can always be made which will give a curve sufficiently straight in the upper section. At times there is evidence that

[1] This is the original equation for plastic flow used by E. C. Bingham in his studies of the plasticity of clay.

very stiff pastes take the form *d*, differing from *c* in the fact that they intercept the pressure axis at a measurable distance from the origin.

The four types of curve given in Fig. 6 apparently represent

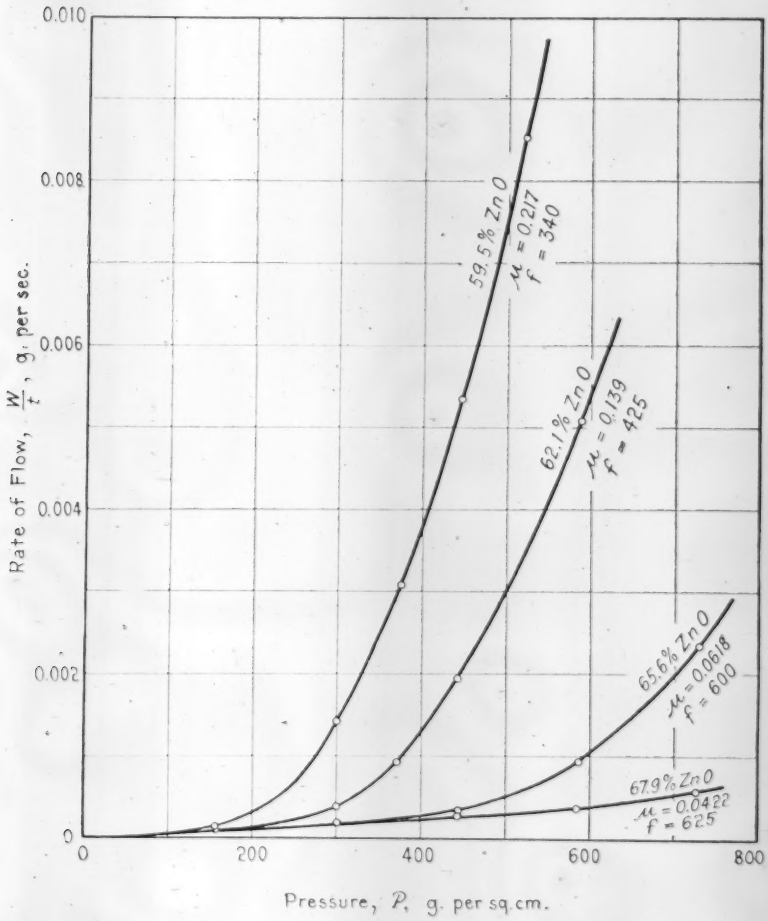


FIG. 7.—Plastic Flow Curves for Some Paint Pastes, Indicating the Result when the Percentage Composition is varied.

the entire field of work. Curve *a* shows that the resistance to viscous flow has but a single factor—the angle the curve makes with the pressure axis. Curve *b* demonstrates the fact that the

resistance to plastic flow is of a *two-fold* nature, depending on the intercept f, as well as on the angle which the curve makes with the pressure axis. It follows that there can never be a true unit of plasticity. The technologist, however, will often state that of two substances one will be more plastic than the other. What he means is, that if the two materials have the same mobility, the one he considers the more plastic will have the greater yield value of the two; while if they possess the

TABLE II.—SOME MOBILITIES AND YIELD VALUES OF COMMERCIAL PAINT PASTES AT 21° C.

No.	Composition of Pigment.	Mobility, μ	$f \times \frac{1}{k}$	Density, ρ, g. per cc.	Condition.
1	100% Zinc Oxide (ZnO) (2.5% Leaded)	0.0102	3.22	2.81	Buttery and very soft.
2	92.5% ZnO, 4.5% Barytes, 3.0% Silex	0.00728	5.08	2.78	Buttery, soft.
3	83.0% ZnO, 17.0% Gypsum	0.00541	9.00	2.44	Thick and buttery.
4	77.0% ZnO, 20.0% Barytes, 3.0% Silex	0.00685	5.55	2.97	Buttery, soft.
5	65.0% ZnO, 35.0% Lithopone	0.00315	9.18	2.95	Thick but very short and buttery
6	100% White Lead C. W. L.	0.000433	4.74	3.98	Thick and buttery.
7	100% ZnO	0.000997	5.29	2.93	Thick, buttery paste.
8	100% ZnO	0.00194	8.25	2.90	Exceptionally fine paste, thick and buttery.
9	100% ZnO	0.000672	4.52	2.88	Thick, buttery paste.
10	.....	0.00109	6.5	.....	Stiff, stringy paste. Drags heavily
11	.....	0.00207	6.81	.....	Stringy, curdled paste.
12	.....	0.000212	4.55	.....	Stiff, stringy paste.

same yield value, the one he considers the more plastic will have a higher mobility than the other.

In Fig. 7 is shown the effect of increasing the percentage of vehicle in a zinc-oxide linseed-oil semi-paste. As the oil content increases, the yield value drops and the mobility rises. If the dilution had been continued further, the form of the curve would gradually assume that of *b*, Fig. 6; and finally that of the viscosity curve *a*, Fig. 6, when the percentage of pigment became negligible.

Some idea of the plasticity of paint pastes may be gained by an inspection of Table II. The great range over which the mobility varies is the most striking feature. The mobility of No. 1 is approximately fifty times that of No. 12. The variation in yield values is not so great, obviously due to the fact that the manufacturer has unconsciously attempted to grind to a constant yield value rather than to constant mobility.

Stiff, stringy pastes are invariably associated with low mobility; but on the other hand low mobility does not necessarily produce stringy pastes. In fact, any pigment capable of being ground in a small percentage of vehicle will give a low

TABLE III.—MOBILITIES AND YIELD VALUES OF SOME GREASES, ETC., AT 21° C.

Kind of Grease.	Mobility, μ	$f \times \frac{1}{k}$	Density, ρ g. per cc.
Arctic Cup Grease No. 0	0.0118	5.30	0.93
" " " " 2	0.000461	6.83	0.93
" " " " 3	0.000324	9.53	0.93
Gredag. No. 57	0.792	0.43	0.90
Transmission Oil; Havoline 600	0.0228	0.053	0.96
Polarine Transmission Grease *BB*	0.0332	0.93	0.90
Keystone Grease No. 3	0.00748	5.96	0.93

mobility. The yield value depends on the wetting of the pigment and its particle size.

Greases.—The subject of greases is very interesting. Unfortunately a lack of time has made it impossible to explore this field to any extent. Anyone at all familiar with the work can see at a glance the highly plastic nature of greases. Their consistency is similar to that of paint pastes, but they differ widely, of course, in density. Table III will give some idea of their nature.[1]

Note the yield value of the transmission of oil. It is so low that it can hardly be called a "grease." Gredag had a consistency somewhat similar to a normal paint.

In Table IV are shown the plasticity factors of a number of paints which are of approximately painting consistency.

[1] The author is indebted to W. H. Herschel for furnishing him with the samples used in this table.

It has been the author's experience that a good paint will have a mobility of 0.200 to 0.500 and a value of $f \times \frac{1}{k}$ of 0.40 to 0.80. No upper limit should be set, however, on the mobility. The higher this factor, the better, if the paint is otherwise good. The high mobility of paint No. 12 indicates an excessive amount of thinners or the use of some unusual vehicle with low viscosity.

TABLE IV.—MOBILITIES AND YIELD VALUES OF SOME PAINTS OF APPROXIMATELY NORMAL CONSISTENCY, AT 21° C.

No.	Paint.	Mobility, μ	$f \times \frac{1}{k}$	Density, ρ, g. per cc.
1	Zinc Oxide	0.204	0.38	....
2	Zinc and Lead	0.373	1.38	....
3	C. W. Lead	0.174	0.51	....
4	Lithopone	0.492	0.79	1.90
5	Lithopone / Leaded ZnO	0.511	0.61	2.09
6	Zinc Oxide / C. W. Lead	0.678	0.34	1.91
7	Zinc Oxide	0.839	0.59	1.59
8	Zinc Oxide, S. W. Lead, Barytes and Asbestine	0.184	0.26	1.55
9	Zinc and Lead	0.266	0.76	1.38
	C. W. Lead	0.286	0.78	2.57
10	Zinc, Lead and Barytes	0.253	0.45	1.92
11	C. W. Lead, Barytes and Asbestine	1.04	0.78	1.94
12	Average	0.442	0.64	

ROUTINE AND RESEARCH WORK.

Each manufacturer devises for himself a particular method of measuring the consistency of his products. The paint man will take the time of flow required for a given volume of material to pass through an orifice of known dimensions; or he will measure the distance that a certain number of drops run on a plate, held vertically, in a definite period of time. More often the question is simply decided by judging the feel and appearance of a product when stirred with a spatula.

Such methods undoubtedly impart useful information to those who have become skilled in the art, but there are times

when they are dangerously misleading. To any one understanding the dual nature of plastic resistance the spatula method is the safest. For instance, the effect of yield value is readily seen when the material is subjected to small pressures, such as its own weight; hence the ease of flow from the spatula gives a fair indication as to the magnitude of this value. The mobility is not so easily judged, but roughly it is inversely proportional to the amount of resistance offered in stirring.

The main drawback to the spatula method is, that the results of the test cannot be recorded in concrete figures and consequently the manufacturer, to whom a barrel of paint has been returned with the complaint that it is "too thin," has but a poor chance to defend his product. It is hardly necessary to point out the many disadvantages in these methods of testing. No definite system of intercomparison has ever been made. While to the individual investigator his own tests give him the information he requires, they mean little or nothing to anyone else. Furthermore, the personal factor plays such an important part in the work that a change in personnel of the testing department cannot help but cause confusion.

With a capillary-tube type of instrument capable of measuring the plasticity factors, all indefiniteness is eliminated. It no longer becomes necessary to employ such vague terms as "body" or "consistency," for yield value and mobility can be defined mathematically. Furthermore, they can be expressed in figures and finally these figures can be duplicated by anybody, with a satisfactory degree of precision.

A plastometer is easily adapted to routine work. The greater portion of the time employed in making a determination is used in filling the container and waiting for it to attain the temperature of the bath. This loss of time may be overcome by having more than one container, and for convenience an extra thermostat. The laboratory helper should prepare the samples and keep the containers clean and filled, so that when the investigator is finished with one, the next is ready for him. A plan like this, if followed out, should not require more than ten minutes for each determination.

The establishment of the method of plasticity measurement opens the way for attacking various research problems, the

solution of which would be otherwise impossible. Matching plastic materials, the ingredients of which are not exactly alike, is probably one of the most important of these. This is usually attained by proper adjustment of the percentage composition of the liquid and solid phases. In spite of the fact that yield value is not a function of mobility, any change that affects the one will usually affect the other. The result of altering percentage composition is seen by referring to Fig. 7. From these curves it is apparent that either the yield value or mobility can be matched separately, but the chance of bringing both to a desired value simultaneously can only take place in those unusual cases where the composition of the ingredients accidentally happens to be right. If the vehicle contains more than one substance, then by a double change, that is in the percentage of vehicle and the percentage composition of the vehicle, it often becomes possible to make a complete match with two different materials.

For instance, a paint with one kind of pigment, A, and a vehicle of linseed oil and turpentine, is to be matched to a paint containing another kind of pigment, B, and vehicle C. Suppose it is found that small additions of linseed oil to the first alters the mobility more than the yield value, and again, that small amounts of turpentine will change the yield value more than the mobility. Under these conditions, by suitable adjustment of materials, a compensation of effects can be produced so that a complete match is possible. The method of procedure is a graphical one and its importance and size is such as to warrant a separate publication in itself. It will not be described here.

In the majority of cases the single matching of either one of the plasticity factors is sufficient to give a desirable product. If such is the case the following method may be used. Suppose the original material to have a yield value f_1 and a pigment-vehicle percentage composition a (Fig. 8). The problem is to find that composition which gives exactly the yield value f_0. The process is simple. Vehicle is added until a rough match is made as estimated by the spatula method. Let the new product have a composition c and yield value f_2. The curve AB is drawn. Assuming it to be straight over short distances, the unknown

percentage composition, b, is obtained by interpolating (or extrapolating) the required yield value f_0. In the same manner mobilities may be matched.

This is a general method applicable to a number of problems. Chief among these are oil absorption of pigments, "degree" of plasticity of clays, and the study of particle size, all closely analogous to the subject of yield value. In addition may be added problems of a different nature such as the thinning of

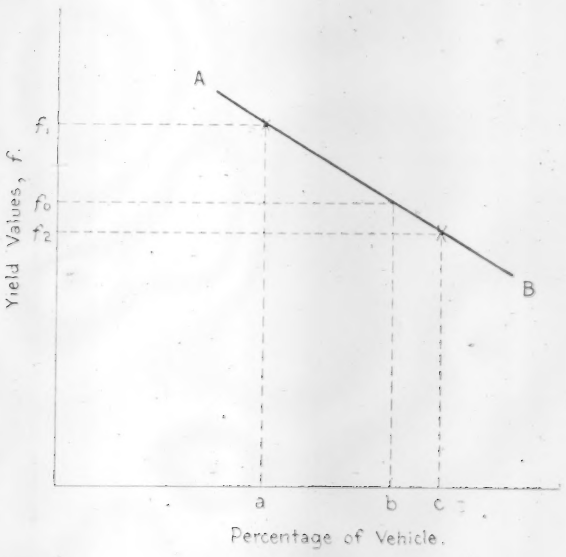


FIG. 8.

paints and pastes upon ageing, livering, stringiness of pastes, and the effect of colloids on the properties of paints. The plastometer cannot solve these in itself but at least it offers a way of measuring their plastic properties which is the first step toward intelligent study and investigation of the subject.

THEORY AND MATHEMATICS INVOLVED IN THE WORK.

Determination of k, the Yield Value Factor.—If the same plastic substance is run through a series of capillaries of different

radii and lengths, it will be observed that the graphically determined yield values, a, b, c, and d vary considerably. (See Fig. 9.) That this variation is due to the fact that the graphical yield

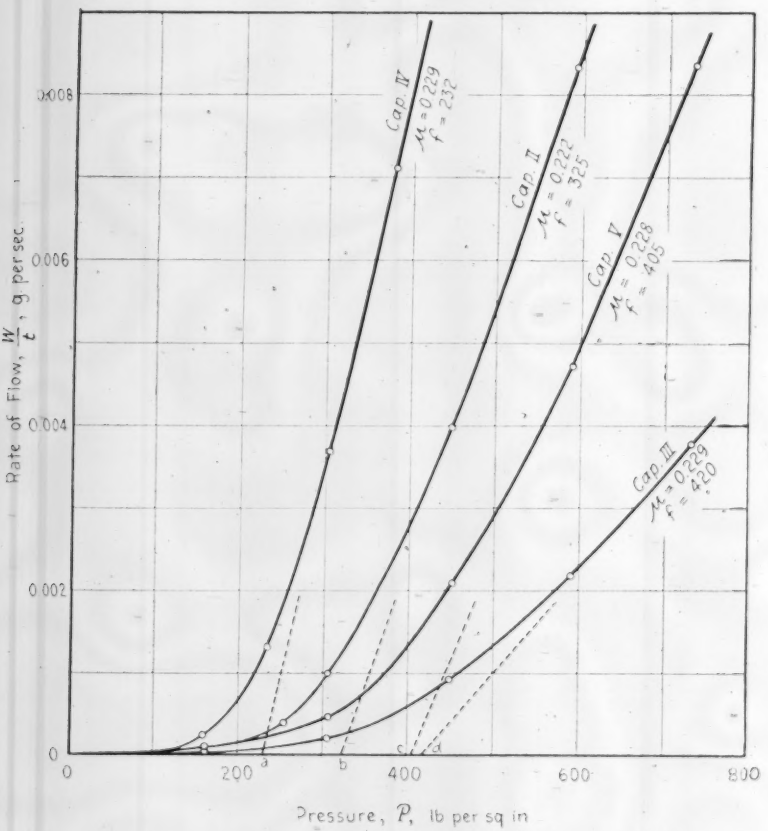


FIG. 9.—Curves Illustrating the Fact That the Graphically Obtained Yield Value Varies with the Capillary Used.

value is a function of the capillary as well as the material itself, is shown by multiplying each intercept a, b, c, and d by its respective r/l,[1] whence a practically constant result is obtained. Yield

[1] The radius of the capillary divided by its length.

values obtained in this way are sufficiently accurate for all practical purposes and the paint man or ceramist needs nothing more if these values ($f \times r/l$) are used in routine or control work. (See Table V.)

It has been noticed, however, that when there is an appreciable change in the length of capillary, the constancy of fr/l is affected in a way that may not be due entirely to experimental error. This condition has been studied graphically and an empirical formula derived whereby a factor, k, can be obtained for any capillary so that the product $f \times \frac{1}{k}$ is constant under all conditions. Mathematical details are omitted. The method in general is as follows:

Two series of capillaries are calibrated, one with varying lengths and the other with varying radii. Let them be represented as,

Series I. Constant Radius.		Series II. Constant Length.	
r_1	l_1	r_1	l_1
r_1	l_2	r_2	l_1
r_1	l_3	r_3	l_1
r_1	l_4	r_4	l_1

It should be observed that there is one capillary common to the two series, the first capillary in each. The solution of the problem depends upon this connecting link. Paints were used for the plastic materials throughout the work.

If the same paint is run through each capillary in Series I, and the graphical yield value, f, obtained plotted against l, the curve produced will be linear and intercept the f axis. Similarly, for Series II, plotting the reciprocal of r against f, the curve will be found to be linear and cut the f axis.

It can also be shown that if a series of different paints be passed through any two different capillaries, and the corresponding graphical yield values plotted against each other, the curve will be linear and pass through the origin.

From these three fundamental facts a factor, $1/k$ can be derived which when multiplied by f will give a constant product independent of the capillary used. It is found that

$$k = (l+\alpha)\ (1/r+\beta) \qquad (6)$$

where α is a function of the radius and β a function of the length of the capillary. Tentative formulas have been derived giving values for α and β where r and l are known.

$$\alpha = \frac{1}{378\,r} + 0.622 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$\beta = \frac{l}{12} + 1.61 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Since the graphical yield values given in Table V were determined before anything was known of the r/l and $1/k$ factors, the results are absolutely unbiased.

TABLE V.—SOME APPLICATIONS OF THE FACTOR k.

Capillary.	Graphical Yield Value, f	$f \times \frac{r}{l}$	$f \times \frac{1}{k}$
V	405	2.12	1.78
II	325	2.18	1.78
IV	230	2.28	1.76
VI	127	0.56	0.47
IV	64	0.63	0.49
S	63	0.198	0.163
VI	46	0.204	0.169
VI	139	0.62	0.51
II	83	0.56	0.45
IV	90	0.89	0.69
VI	177	0.79	0.65
IV	85	0.84	0.69
VI	182	0.81	0.67

An Analysis of the Plastic Flow Curve.—It has been pointed out earlier in this paper that there is a decided departure of the experimentally obtained plastic flow curve from that of the ideal one, mathematically derived. (See Fig. 6, *b*.) It will be recalled that in the straight sections the two curves coincide but where the pressures become comparatively low, coincidence ceases, the experimental curve bending toward the origin and the other continuing linear.

As no apparatus has been devised for measuring rates of flow under very low pressures it cannot be ascertained that the curve actually passes through the origin. But while there is no

proof that it does, it is equally true that there is no proof it does not; hence a double possibility. If the former condition should be the fact, then an infinitely small force will cause deformation in a plastic substance as well as in a liquid and the fundamental difference, by definition, between these two classes of materials is nullified. Furthermore, it would indicate that the true yield value is a variable, a purely dynamic affair, depending upon the velocity of the material under flow. For these two reasons is it desirable to investigate the subject more fully.

The so-called elastic limit of metals varies with the rate of application of the load. The explanation is evident. From the laws of viscous and plastic flow the *amount* of permanent deformation under a given pressure is directly proportional to the time involved. More time is consumed in applying a certain stress at a lower rate of application than at a higher one, hence the amount of deformation is greater and the elastic limit is lower.

It is clearly untenable that such a condition exists, causing a variable yield value in the plastic flow curve. The curve is a graphical means of expressing the relationship between the rate of flow and the pressure. Anything that does not enter into these two variables naturally cannot affect the curve. The pressure is manometer reading, in which the element "time" does not enter. The rate of flow is a constant, under constant pressure, and absolutely independent of the time. Briefly, the amount of flow in the elastic limit determination is replaced here by *rate* of flow, and all analogy ceases.

It is reasonable to believe that there is an invariable property inherent in plastic materials which governs the magnitude of the true yield value. A question now arises. Is the constancy of this property affected by the velocity of the material under flow? If so, it can only be in that region of low pressures where the curve departs from its natural linear course. It has already been demonstrated that the true yield value is independent of the capillary.[1] Now the velocity of the material for any given volume of flow is:

$$\text{Velocity} = \frac{V/t}{\pi r^2} \qquad (6)$$

[1] This is seen from the fact that the *graphical* yield value can be converted to a constant, independent of the capillary employed. Table V.

Therefore it follows that two capillaries may be so chosen that the velocity in the straight portion of the curve for one is exactly equal to the velocity in the curvilinear portion of the other. Such being the case no relationship can ever exist between velocity and true yield value. (See Fig. 10, *a* and *b*.)

By examining under a microscope the flow of plastic materials through capillaries, a satisfactory solution of the problem has been attained. The capillaries used in the plastometer are thick walled and not suitable for microscopic observation. Ones with sufficiently thin walls may be made by drawing out ordi-

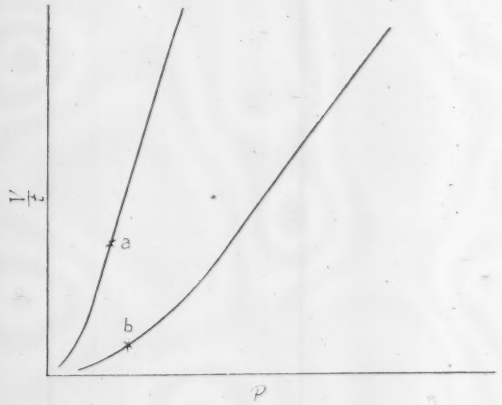


FIG. 10.—The Velocity at *a*, from which the True Yield Value is Determined, is the Same as That at *b*.

nary glass tubing to a desired degree. These are then cemented to a microscope slide. (See Fig. 11.)

The capillary portion of the tube is at *c*. A rubber tube, *b*, is fastened on the large end. A block of DeKhotinsky cement, *d*, holds the tube in place.

A paint of suitable yield value is rubbed down with enough ultramarine to give it a pronounced bluish tint. This material is added because it is easy to distinguish under the low magnification used, while the paint particles are not. Some of this paint is sucked in till it reaches the mark *a*. Upon microscopic examination a number of facts will be observed. First, that the

vehicle wets the walls of the tube; second, that the pigment touches the walls at but very few points; third, that the paint exists as a mass of "interlocking flocculates." If a light air pressure is now applied at *b*, the material will be set in motion; the entire mass, being held together by interlocking of the flocculates, will move in one solid block. The phenomenon is analogous to that of pushing a lead pencil through a glass tube. The application of high pressure brings about an entirely different state of affairs. Under this condition the flocculates are broken up and, upon observing the ultramarine particles, it will be noticed that the paint is now moving in telescopic layers, the inner ones at a much greater velocity than the outer ones.

It is apparent from this that the plastic flow curve should indicate two types of motion; one, a motion *en bloc* and the

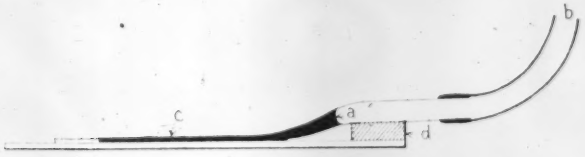


FIG. 11.—Apparatus for the Microscopic Observation of Plastic Flow Through Capillaries.

second, true "fluid" motion. Referring to Fig. 6, *c* and *d*, it will be seen that this is exactly what happens. Note the two straight branches of each curve, signifying clearly the existence of two kinds of flow. The curvilinear section represents the transition of one flow into the other, and constitutes a mixed "regime." An inspection of the linear portions of the curve substantiates the visual evidence obtained with the microscope. Take the lower branch first. Here the pressures are low and the paint moves as a single block. As a model, imagine a solid metal cylinder, lubricated with a thin layer of oil, fitting snugly into a tube. As oil is a liquid it must obey the viscous law; therefore, if air pressure is applied to the tube the cylinder will move through it with a velocity directly proportional to that pressure.[1] If the cylinder is a continuous affair then its volume

[1] After the acceleration has become zero.

extruded from the end of the capillary tube, per second, will also be directly proportional to the pressure. A pressure rate of flow curve so derived will be linear and start from the origin. (See Fig. 6, *c*, lower branch.) If the lubrication is not complete and there is friction between the cylinder and the tube the pressure axis will be cut at a finite distance from the origin. (Fig. 6, *d*.) This is the first coordination of facts.[1]

With Eq. 4, the mobility is derived, using the measurements from the upper branch of the curve. Mobilities obtained in this way are independent of the capillary. (See Table VI.) This being a fact, the curve at this section follows the law of plastic flow; but the law is derived on the assumption that flow

TABLE VI.—THE MOBILITIES OF FOUR DIFFERENT PAINTS, SHOWING THE CONSTANCY OF RESULTS WITH DIFFERENT CAPILLARIES.

	Capillary.	Mobility.		Capillary.	Mobility.
(I)	VI	0.684	(II)	VI	0.664
	III	0.683		III	0.702
	II	0.684		II	0.666
	VII	0.685			
(III)	IV	0.480	(IV)	IV	0.335
	II	0.488		II	0.326
	V	0.481		V	0.330
	VIII	0.474		VIII	0.328

takes place in telescopic layers. This is a second coordination of facts. Briefly, the analysis of the curve is in agreement with the conditions observed under the microscope. With low pressures a false type of flow, "slippage," takes place, introducing a divergence between fact and theory.

The next step in the problem is to show that slippage is due to what may be termed a defect in the instrument. The viscous law, Eq. 1, assumes that for liquids slippage does not take place. That the law holds is proof of the correctness of this assumption. There are only two possible reasons for this. Slippage is either prevented by (*a*) the molecular attraction between the glass walls and liquid being sufficiently great or else (*b*) the walls of the capillary present a rough surface to the molecules of the liquid.

[1] That is, between those facts observed with the miscroscope and those derived from an analysis of the plastic flow curve.

That neither of the above conditions prevail for paint is quite evident. Pigment particles are large in comparison with molecular dimensions, and the glass must act as a smooth surface toward them. Furthermore the particles of pigment do not come in close enough contact with the walls of the tube to permit adhesive forces becoming effective. The only reason that the particles are retained at all is due to the viscous resistance of the thin layer of oil existing between them and the capillary walls. Any small pressure will cause this layer to flow, producing slippage. When the pressure becomes greater than the true yield value an internal yield takes place in the paint, and the total flow becomes disproportionately greater than the pressure otherwise would warrant. Here the curve begins to bend upward. As the pressure increases the percentage of slippage

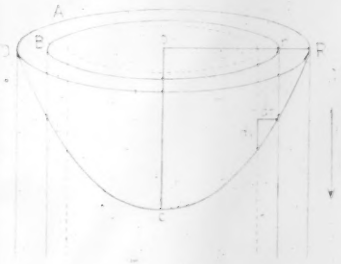


FIG. 12.

decreases, and in the straight part of the curve the slippage is assumed negligible.

The capillary-tube type of plastometer cannot prevent slippage. Slippage of this type is, therefore, only an instrumental effect.

The point may well be raised that flow of some kind actually does take place below the yield value; that this is the only thing of practical importance; that it is immaterial what name is given to it or how it is explained. The answer to such an argument is that this type of flow is highly conditional, depending on the fact that it takes place *through a glass capillary tube*, and is not analogous to anything ever met with in painting practice. In addition, a paint so constituted that it runs off a wall does not "slip" but "flows," signifying an internal yield.

The determination of a yield value is, therefore, of practical consequence.

A summary of the evidence in justification of the assumption that the graphical yield value, determined by extrapolating to zero rate of flow, possesses a real value, follows:

1. The introduction of a constant yield value into the viscous law produces the law of plastic flow. The law of plastic flow states that a complete linear relationship must exist between P and V/t.

2. The yield value is independent of the velocity of the material under flow.

3. The instrumental effect, slippage, is sufficient in itself to explain the variance between the theoretically and experimentally derived curves.

Mathematical Derivation of the Law of Plastic Flow.—The coefficient of viscosity definition may be expressed in the form of an equation,

$$\eta = \frac{F}{v/r} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where η = viscosity, F = shearing force per square centimeter necessary to overcome viscous resistance, v = velocity of displacement between any two layers of the liquid, and r = distance between the two layers. Then,

$$\frac{\delta v}{\delta r} = \phi F \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where ϕ = fluidity.

For plastic materials, let s equal the shearing force per square centimeter necessary to start flow. Then the force used to overcome plastic resistance will be $F-s$, and

$$\frac{\delta v}{\delta r} = \mu (F - s) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)^1$$

A pressure, P, is applied to the end of the capillary, A, Fig. 12, causing a flow in the direction indicated. Let OC represent the

[1] Eq. 12 does not refer to flow through a capillary tube, but to the customary model of flow, which is supposed to be bounded by two parallel planes, the lower one stationary and the upper one moving. In such a case, r is measured upward from the stationary plane and the velocity gradient is positive. When the flow takes place through a capillary tube, r is measured from the center outward and the gradient becomes negative as in Fig. 12.

velocity at the center. If the flow is telescopic and no slippage takes place, the velocities in cross-section will be given by the curve RCD. Let R be the radius of the capillary and r the radius of an imaginary cylinder B. It follows from Eq. 12 that

$$\frac{\delta v}{\delta (R-r)} = -\frac{\delta v}{\delta r} = \mu (F - s) \ldots\ldots\ldots\ldots (13)$$

The total force exerted on the end of cylinder B, is equal but opposite in direction to the total force of plastic resistance on the lateral surface of the cylinder.

Then, $$\pi r^2 P = -2 \pi r l F$$

and, $$\pi r^2 f = -2 \pi r l s,$$

where f is the end pressure force corresponding to a shearing force s.

Therefore,

$$F = -\frac{r}{2l} P \ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

$$s = -\frac{r}{2l} f \ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Substituting then in Eq. 13, gives,

$$\delta v = \mu \left[\frac{r}{2l} (P - f)\right] \delta r \ldots\ldots\ldots\ldots\ldots (16)$$

The volume of flow per second, V/t, is given by the equation,

$$\frac{V}{t} = \pi \int_0^R r^2 \, \delta v$$

Then,

$$\frac{V}{t} = \frac{\pi \mu (P-f)}{2l} \int_0^R r^3 \, \delta r = \frac{\pi \mu R^4 (P - f)}{8 l}$$

or,

$$\mu = \frac{8 l}{\pi R^4 g} \frac{V/t}{(P - f)} \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

A certain portion of the pressure P is used in imparting kinetic energy to the material. This has been calculated by various investigators and is approximately equal to $\frac{(V/t)^2}{\pi^2 R^4 g}$.

If this amount is appreciable, it should be subtracted from each pressure before plotting for yield value or calculating mobility.

CONCLUSION.

In writing this paper the author has endeavored to present the subject in such a manner that the ideas involved could be understood by anyone who had not previously read the literature introductory to it. At the same time an attempt has been made to avoid an unnecessary repetition of material already published.

Due to inquiries received in regard to the construction of a plastometer, descriptive details have been included that otherwise would be omitted. The method of operating the instrument has been materially changed from that described in the original paper. Various ways were tried to determine the rate of flow of the material being tested, by measuring the volume of air it displaced from G, Fig. 2, in a given time. These attempts proved to be unsatisfactory. The author is indebted to Mr. W. C. Harpster for the suggestion that a gas flowmeter might be constructed to record rates of flow so small that it would be possible to apply it in this case. The suggestion was found practical. The addition of the flowmeter eliminates the drop method entirely. On account of this, it is no longer necessary to make an accurate density determination; nor is it necessary to remove the container from the thermostat during operation.

The mathematics involved in plasticity determinations has been reduced to simply the use of Eq. 4. A curve with its linear portion within the limits of pressures given by the stabilizer can always be secured with a proper selection of capillary.

Acknowledgment.—The author wishes to express his appreciation to Dr. E. C. Bingham for the helpful advice received from him during the development of the work described in this paper.

DISCUSSION.

Mr. Herschel.

MR. WINSLOW H. HERSCHEL (*presented in written form*).— There are one or two points which are not clear in regard to the measurement of the head acting on the main capillary *F*. As the scale *O*, in Fig. 2, does not extend above the bottom of the capillary, the discharge is never submerged and therefore the flow can not be influenced by the rise of level in the receptacle *G*. Then the manometer shown in Fig. 3 is not located in Fig. 4, and it is therefore not clear whether the comparator reading *H* is subtracted from the manometer reading, or whether the manometer is connected across between *A* and *B* in Fig. 4 so that the manometer reading is automatically corrected. Nothing is said about the effect of temperature changes on the reservoir *X*. It would seem desirable to place *X* in a water bath whose temperature would be sufficiently constant during any one test without control. Otherwise it would be of interest to know the maximum allowable length of run or maximum change of room temperature which would be permissible.

As explained in previous papers, Eq. 1 is not complete. The kinetic energy correction, as given on page 482, would in all probability be more accurate if multiplied by 1.12. The Couette correction is entirely omitted. This latter correction is a function of the diameter and must be added to the measured length of capillary to get the effective length. It seems possible that if the Couette correction were introduced, the work of finding *k* could either be omitted or simplified.

In regard to slip at low rates of shear, it is of interest to know that the MacMichael instrument has been used by Perrott and Thiessen[1] to prove that certain substances are plastic and that in general there is a straight line relation between speed and deflection, but the points at lowest speeds show less deflection than indicated by an extension of the straight lines.

The tests on greases are of great interest, but I question the propriety of melting samples before placing them in the

[1] *Journal Ind. and Eng. Chem.*, Vol. 12, p. 324 (1920).

Mr. Herschel. container, since the consistency of a grease is permanently changed by melting. However, it is not believed that this would substantially change the comparative results of the tests given in Table III, which shows a very great difference in consistency between two No. 3 greases. If we may assume that different grease manufacturers try to make their No. 3 greases of the same consistency, these results show the utter failure of the spatula or similar tests to accomplish this result, and show the great need of standardizing the yield point and mobility of greases.

Mr. Green. MR. HENRY GREEN (*presented in written form*).—The rise in level in the receptacle, *G*, referred to by Mr. Herschel does *not* influence the hydrostatic head in the container; it only indicates how much material is left in the container. The height of this material plus the length of the capillary multiplied by the density gives the hydrostatic head to be added to the main pressure. The actual fall in head during the determination of each point on the plastic flow curve is generally about 1 or 2 mm. and consequently nothing would be gained by attempting to ascertain an average head during the course of such a determination. The magnitude of the total pressure used is very great in comparison with this slight correction.

The manometer shown in Fig. 3 is not a part of the flowmeter and consequently is not shown in Fig. 4. For the method of connecting it to the instrument reference must be made to Fig. 3 of last year's paper.[1] In some cases the comparator reading, *H*, may be used as a slight correction to be subtracted from the pressure given on the mercury manometer. In the case of plastic materials, however, low pressures dare not be employed, and the ratio of oil head to mercury head is so small that this correction becomes negligible.

The main object of *H* is to obtain the volume of flow of the material as it is forced through the capillary. I have pointed out in Eq. 3 and in the last paragraph of page 462, that, if *H* is multiplied by the flowmeter constant, *C*, the product will be the rate of flow, V/t.

[1] E. C. Bingham and Henry Green, "Paint, a Plastic Material and not a Viscous Liquid: the Measurement of its Mobility and Yield Value," *Proceedings*, Am. Soc. Test. Mats., Vol. XIX, Part II, p. 640 (1919).

Mr. Green. This is simply a quick and accurate method for determining the rates of flow which, when plotted against their corresponding pressures (determined by the manometer, Fig. 3), produces the plastic flow curve.

In the apparatus which I have constructed at Palmerton the six flasks comprising reservoir X are contained in an oak box tightly closed. I find that this insulation is sufficient. On page 464 it is stated that it takes about one minute for the flow-meter to come to equilibrium. On page 458 you will note that stopcock W is opened after each reading, preventing an accumulation of pressure in X. From these two facts it is evident that unless the fluctuation in room temperature is very abnormal, say several degrees a minute, no water bath would be necessary for the purpose of temperature control.

As far as the kinetic energy correction is concerned I can safely say that in the majority of cases it is quite negligible. For instance, the greatest rate of flow in Table I is 0.00962 cc. per second. In round numbers call it 0.010 cc. per second. The radius of the capillary is 0.014486 cm. Then

$$\frac{(V/t)^2}{\pi^2 R^4 g} = 0.23, \text{ and } 0.23 \times 1.12 = 0.26.$$

The pressure used at the time was 581.00 g. per sq. cm. It follows from these figures that the particular error introduced at this one point on the curve, due to neglecting the kinetic energy correction, is only 0.047 per cent. It should also be borne in mind that an error of 0.047 per cent in one point on the curve does not necessarily introduce an error as great as this in the yield value and mobility.

When the plastometer is used as a viscosimeter, or if a high degree of accuracy is desired in mobility determinations, it is then certainly advisable to introduce the Couette correction in the calculation of the capillary constant, K. I cannot see that it would be a legitimate procedure to use this same correction in connection with the yield value, and, even if it were employed, the product $f \times \frac{r}{l}$ would still vary. The reason for this inconstancy is, more likely due to the fact that, theoretically, the

Mr. Green. pressure–rate-of-flow curve is only straight at infinitely high pressures. I have read with interest Perrott's and Thiessen's article on the application of the MacMichael instrument to plasticity determinations. I have come to the conclusion that their deviation from the straight line relationship is also due to slippage; in fact I cannot conceive of an instrument which will not have this fault.

I agree with you on the impropriety of melting greases before determining their yield values and mobilities. This is a problem, however, which must be solved by those who are more vitally interested in greases than we are at Palmerton. As you can readily understand, this branch of the work has been purely a side-issue with us.

Mr. Bingham. MR. E. C. BINGHAM (*presented in written form*).—With the wealth of detail of Mr. Green's paper before us and in view of the perfectly proper emphasis which he has placed upon precision of measurement, the simplicity of the conclusion of the matter deserves a word of emphasis.

When a plastic material is subjected to a shearing force F, in dynes per square centimeter, no permanent deformation will result under ordinary conditions until the shearing force exceeds a certain value f, known as the *friction* or *yield shear value*. We then define the mobility, μ, of a plastic material as the velocity given to a layer of the material in respect to another layer one cm. distant, when the shearing force in excess of the friction, $F - f$, is one dyne per sq. cm. Making assumptions entirely analogous to those made in viscous flow, we may express our fundamental definitions, as applied to an elemental volume of material in the following formula:

$$dv = (F - f)\, \mu\, dr \qquad (1)$$

where dv is the differential of the velocity of one layer in respect to another layer separated from it by the distance dr. It is to be noted that the shearing force F is the same at every point of the material and is, therefore, independent of r.

Since, however, one ordinarily measures not the shearing force, but the pressure P in grams per square centimeter required to cause a given rate of flow through a capillary tube, confusion may easily result. For example, it has been shown that by

plotting volume of flow against *pressure*, the pressure p required to start the flow is not constant but dependent upon the dimensions of the capillary R and l in centimeters. What this function is will now be indicated. Mr. Bingham.

The total shearing force producing the flow, when the flow is just about to start, is $2 \pi R l f$ and this force is derived from the pressure which is $\pi R^2 p$. When the flow is established we have $2 \pi R l f = \pi R^2 p$, hence we have the relations $f = \frac{p R}{2 l}$ and $F = \frac{P R}{2 l}$. The volume of flow through a capillary tube $\frac{V}{t}$, may be obtained from Eq. 1 by integrating from the center of the capillary where $r = 0$ to the wall where $r = R$ as follows:

$$\frac{V}{t} = \pi \int_0^R r^2 dr = \frac{\pi \mu (P - p)}{2 l} \int_0^R r^3 dr = \frac{\pi \mu (P - p) R^4}{8 l}$$

hence

$$\mu = \frac{4 V}{\pi R^3 (F - f) t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Since, as indicated above, the shear is independent of the dimensions of the capillary, if we use Eq. 2 plotting V/t against F, we will obtain for different capillaries a series of straight lines which meet at a common point at a distance f from the origin. For different radii, the curves have different slopes. If, on the other hand, one plots V/t against P, he finds that the apparent yield pressure p is variable, being in fact $p = \frac{2 l f}{R}$, that is, the yield pressure varies directly as the length and inversely as the radius of the capillary.

Table I shows how well the observed data accord with the values predicted by the theory. It is now clear that in the analysis of data for plastic substances we should compare volume (or weight) of flow with the *shear*, $F = \frac{P R}{2 l}$, when the true friction can be obtained at once.

Mr. Bingham.

The friction may be obtained graphically or by means of the formula:

$$f = \frac{F_2 V_1/t_1 - F_1 V_2/t_2}{V_1/t_1 - V_2/t_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where V_1/t_1 is the volume of flow in cm.^{3} per second when the shear is F_1 dynes per sq. cm. and V_2/t_2 is the volume of flow when the shear is F_2. Taking the average friction, the mobility may then be calculated by Eq. 2. It is, therefore, theoretically possible now to measure the plasticity of a substance by making two measurements of the flow using merely a single capillary.

Whereas the data, as published, gave values for the friction which vary widely for the *different* capillaries, Table I shows that this is no longer the case. There is more variation for a single capillary at different pressures than there is for the different capillaries. The remaining variation may be best avoided by using larger pressures.

TABLE I.—FRICTION AND MOBILITY OF A PAINT.

Observation No.	V/t, cm.^{3} per sec.	P Pressure in g_w per cm.^{2}	$F = \frac{PR}{2l}$ dynes per cm.^{2}	f, dynes per cm.^{2}	$F - f$	μ	Remarks	Observations used in calculations.
1	0.0005836	670.8	1030.7	98.2	938.7	0.260	Capillary S	1 and 2
2	0.0001557	537.8	826.3	84.6	734.3	0.260	$R = 0.014486$ cm.	2 and 3
3	0.0003344	409.3	628.9	75.9	536.9	0.261		3 and 4
4	0.0002133	277.5	426.4	66.0	334.4	0.267		4 and 5
5	0.0001661	225.6	346.6	57.7	254.6	0.273		5 and 6
6	0.0001019	152.9	234.9					
7	0.002424	670.2	1458.6	101	1366.6	0.253	Capillary VI	
8	0.001942	538.5	1171.9	85.4	1079.9	0.254	$R = 0.020805$ cm.	9 and 10
9	0.001418	409.5	891.2	87.5	799.2	0.255	$l = 4.684$ cm.	10 and 11
10	0.0008987	274.3	596.9	65.6	504.9	0.256		11 and 12
11	0.0004164	143.3	311.8	53.7	219.8	0.272		
12	0.0002880	105.7	232.2					
13	0.004628	671.7	1723.0	81.6	1641.0	0.246	Capillary III	13 and 14
14	0.003678	539.1	1387.9	92.2	1299.9	0.246	$R = 0.02450$ cm.	14 and 15
15	0.002726	399.0	1049.2	85.1	957.2	0.246	$l = 4.681$ cm.	15 and 16
16	0.001758	275.6	705.9	75.1	614.9	0.247		16 and 17
17	0.0008267	145.1	372.2	63.5	280.2	0.255		17 and 18
18	0.0005856	110.0	282.2					

The average friction obtained graphically used in calculating the mobility is 92.0 dynes per cm.^{2}, which gives an average mobility of 0.257. When the rate of flow V/t is too small, the friction becomes smaller, as seen in the table and the last two values for each capillary may well be neglected.

Mr. Thompson.

MR. G. W. THOMPSON.—At last year's meeting I raised a question with reference to a similar paper which was presented at that meeting, and in my question I referred to the previous

work which had been done by Mr. Bingham. I did not get a satisfactory answer last year, and perhaps it will be impossible to get one this year; but the question is one that forces itself upon me, not because of its direct practical value, but because if answered, it would help in the understanding of the problems which are treated in this paper. Mr. Green says that paints are plastic materials. Perhaps this may serve partially as a definition of paint. Mr. Bingham, in his earlier papers, made a distinction between solid and liquid mixtures of low concentration, as far as the solid is concerned, and mixtures of high concentration; and, if I remember correctly, he stated that as the concentration increased, up to a certain point, the mixtures followed the law of viscous flow, and that above this point the mixtures followed the law of plastic flow. In the case of any given pigment there will be, therefore, a point of concentration below which it will follow the law of viscous flow, and above which it will follow the law of plastic flow. It may be that the work which has been done more recently along this line has resulted in a revision of the opinions then expressed by Mr. Bingham, and it may be that with even a very low concentration of pigment you still have a species of plastic flow, but recent investigations do not emphasize this point or make clear that there is any definite change from the opinions originally expressed by Mr. Bingham. I wrote to Mr. Bingham last year, suggesting the desirability of establishing a test which could be applied to pigment, and which, if carried out under standard conditions, would enable one to determine the limit of concentration within which viscous flow would take place. If such a test could be devised, we would get a set of specific figures with regard to pigments, so that they could be compared, and we could have some conception, at least in numerical form, of the fineness of the pigments. I would like to bring this question up again and again because I believe that if such a test could be developed much valuable information would be obtainable. To explain the point more fully in the case of viscous flow: if flow is plotted against pressure, we have a straight line, one end of which terminates in the origin. In the case of plastic flow we get, above a certain point, a straight line which, if prolonged, intersects the horizontal axis at a measurable distance from the origin.

Mr. Thompson.

Mr. Thompson. As I have before stated, Mr. Bingham claimed, in an earlier paper, that, up to a certain point of concentration, solid-liquid mixtures followed the law of viscous flow, and above that point they followed the law of plastic flow; and the two lines I have described represent these two types of flow. It may be that the test which I have suggested cannot be applied for the reason that perhaps the two lines representing viscous and plastic flow are not so different as would at first appear, for it will be observed that in the case of plastic flow, while it is true that a straight line, if prolonged, does not pass through the origin, still at low pressures there is a bending of this line so that apparently it, too, passes through the origin. It seems possible that the point at which this line bends will vary in point of elevation inversely with concentration, and if the concentration is low enough, this point of bending will be so high in elevation as to be indeterminable. There is another way to consider this proposition—in the case of plastic flow where flow is plotted against pressure we get a curve having a bend. Above a certain point it is a straight line. At that certain point the line bends toward the origin. It would seem possible, therefore, to determine the angle of bend, which should bear some relation to concentration.

I want also to refer to something that is a little confusing in my mind in one of Mr. Green's illustrations. He stated that when zinc oxide was rubbed up with water so as to obtain a very stiff mixture, the particles were flocculated in the mixture, but that if to the mixture was added a small amount of gum arabic, the particles became deflocculated and he obtained a more fluid mixture. There is something that appears to me contradictory in his argument. As I understand it, according to the latest teaching of colloid chemistry, flocculation is equivalent to a reduction of dispersion, and deflocculation is equivalent to an increase in dispersion. In other words, when particles flocculate you get the equivalent of coarse particles. When you deflocculate you get the equivalent of fine particles. In the example given by Mr. Green it would appear that with deflocculation you got the equivalent of coarse particles. In the experiment which Mr. Green recites it would appear, therefore, that the addition of gum arabic tended to make the particles coarser, or something equivalent to this, unless, indeed, there is some other factor involved which has not yet been considered.

MR. HENRY GREEN.—It seems to me that the mere mechanical process of flow cannot be any different in the case of plastic substances than it is with viscous liquids. That is, that with either material, under the conditions of the experiment, flow will take place in parallel cylindrical layers, with the innermost layer traveling the fastest and the outer one the slowest. Hence the *flow* of a plastic substance is always *viscous flow*, and it is obviously incorrect to speak of "plastic flow", if we wish simply to imply that the material undergoing flow itself is plastic. Mr. Green.

For any given pigment and vehicle, however, it is always possible to have a mixture of the two, such that the resulting compound will be exactly on the border line between the viscous and plastic states. How sharply this point can be determined still remains to be seen. At present very little work has been accomplished in this direction. I would like to add in regard to particle size, that in working with zinc oxide (and presumably it will be the same for other materials) I have found that the finer grained the material the higher yield value it will give, other things being equal.

In regard to the point which Mr. Thompson has discussed, concerning the possibility of curves, derived from mixtures with very small pigment content, being in reality plastic and not of the viscous type, I can state several reasons for believing this not to be the case.

First, if the point of maximum curvature receded from the origin when the percentage of pigment decreases, as suggested, then it follows that the lower or slippage branch of the curve increases in length, which means that slippage will be at its greatest with a material that is 100 per cent pure liquid. This is contrary to the facts discovered by other investigators. Furthermore, as I endeavored to point out in my paper, slippage is caused by the pigment particles being closely packed together and, unless the force that moves them through the capillary is greater than the yield value, the paint will not split up into telescopic layers but move in one solid block, which is slippage. Slippage increases, therefore, only with *increase* in percentage composition of pigment. Such being the case, it seems justifiable to assume that any straight curve cutting the origin does not possess a point of curvature outside the range of our measurements.

Mr. Green. The last point raised by Mr. Thompson is the question of the deflocculation of paints. From his point of view deflocculation should produce a stiffer paint (that is, one with a higher yield value). This might possibly be a fact when the percentage of pigment is very small. For instance, take an imaginary case of a vehicle in which only two pigment particles are suspended. If this mixture is subject to flow and the first particle in passing the second one rubs against it, an exceedingly small amount of yield value will result. Now, if flocculation had taken place, there would have been practically only one particle present and the yield value would have been zero. In other words flocculation here produces a thinner paint.

In a material of painting consistency, however, the flocculates are large in size and irregular in form and so closely packed that they interlock. This interlocking produces a structure of sufficient rigidity to produce a yield value. When deflocculation takes place this structure is completely demolished and the yield value consequently is lowered. This is not a matter of theory. It can be easily verified with the microscope. Perrott and Thiessen have come to similar conclusions in their recent work with carbon blacks.

As to the matter of a dispersed mixture having an increased surface action, I find it difficult to reply, for I do not understand what Mr. Thompson means by "surface action." If this expression refers to surface energy, then I would answer that the addition of a deflocculating agent always decreases the energy in the solid liquid interface, as is well known. On the other hand, if something like gravitational attraction is referred to, then it is evident that no matter how great this force is, if it does not cause flocculation, it cannot affect the yield value, for the resultant of all such forces acting on each individual particle must be zero or otherwise the material would not be in equilibrium.

Mr. Bingham. MR. E. C. BINGHAM.—There are two methods for getting the concentration which serves to demarcate the fluid from the solid state, which we may speak of as the concentration of zero fluidity or the concentration of zero friction. We may decrease the friction of suspensions by adding more and more of the liquid medium until we obtain the concentration where the

friction is zero, or we may determine the fluidity of suspensions containing more and more of the solid until the fluidity (extrapolated) becomes zero. Mr. Bingham.

In reference to the first method, the above table shows that the friction, when it is so very small as it is in paint, is subject to considerable percentage variation, due partly to the fact that the individual values are obtained by extrapolation. This is of no great moment apparently, since the differing values lead to closely agreeing values of the mobility and probably of the concentration of zero fluidity too.

The second method seems simple and may become very useful, but it has a theoretical difficulty which I may be pardoned for proposing here. It has not been conclusively proven that the viscosity of a suspension is not dependent upon the dimensions of the viscosimeter. Experiments by Mr. Kleinspehn and myself at Lafayette College give ground for believing that this may be the case, particularly with viscous media such as linseed oil which make necessary the use of short and wide capillaries.

Mr. Thompson does a real service in fixing our attention upon the possibility that the concentration of zero fluidity is a third variable which may be independent of both the friction and the mobility of a given paint. It therefore may give equally important information in regard to the nature of the paint.

MR. R. E. WILSON.—In connection with the foregoing discussion I would like to point out that there is really no possibility that the plastometer curve for low concentrations has a point of inflection beyond the limits of the chart, because the point of inflection comes *lower* as the concentration decreases. The hypothesis suggested by a previous speaker could, therefore, not possibly be true. Mr. Wilson.

To answer another question—what is the real effect of this gum arabic in greatly increasing the fluidity of a given paint mixture? I think Mr. Green's explanation is essentially correct, but might be made clearer by picturing just what happens. When particles flocculate, they do so because there is an attractive force between them. We know very well that solid particles tend to have a great attraction for one another and that they tend to absorb colloidal particles on their surface. If we cause

Mr. Wilson. a suspension of such particles to flow, we must move particles, which have a mutual attraction, past one another and we cannot do this without doing work. When we put gum arabic into the suspending fluid, it is absorbed on the solid particles and neutralizes the attractive forces. If we now move one particle past another, we can do it without the expenditure of work; that is why we find that the addition of a protective colloid does decrease yield value and increase fluidity. This in no way invalidates Mr. Bingham's statement that the finer a pigment is ground, the less is the fluidity of the resulting paint, other things being equal. Every new surface which is exposed must be covered with a film of oil which naturally decreases the amount of free oil present and hence decreases the fluidity. To summarize, a paint suspension may be made finer in either of two ways: by adding a protective colloid, which tends to neutralize the attractive force between particles, breaks up agglomerates, but creates no new surface; or by grinding, which increases the amount of surface without affecting the attractive forces between the particles. The first method increases, while the latter decreases, fluidity.

It appears to me that this work of Mr. Green is of most fundamental importance in a wide number of fields. There is scarcely anything about which greater confusion exists in many different industries than this question of body, plasticity, mobility or whatever we may call it. The clay people have one idea, the paint people have another, the starch paste people another, the rubber cement people still another. Different committees are talking about plasticity and meaning entirely different things. Furthermore, from the discussion going on in the lobby, I know there are quite a number of members who are planning to apply this type of investigation to their particular fields. I wonder if that work would not be much more effective and helpful if a committee of the Society could be appointed to try out this device for the different fields, like clay, lime, starch paste, rubber cement, etc., in order to get a series of values and then try to define terms, as Mr. Green has given us the opportunity to do? If a meeting should be called of those interested, I think it would be very helpful, unless Mr. Green himself plans to go into all these different fields.

TESTING OF POROSITY OF ELECTRICAL PORCELAIN.

By W. D. A. Peaslee.

One of the most important requirements for porcelain used in the electrical industries is an absolutely non-porous structure. The many articles appearing in the Proceedings of the American Institute of Electrical Engineers, as well as in other engineering literature in the past few years, show the increasing realization of this fact on the part of engineers concerned with the use of porcelain insulators, especially at the higher voltages (22,000 volts and upwards).

The effect of porosity on insulator porcelain is manifested in a lowering of the ohmic resistance. This is due to the moisture absorbed by the porcelain, which, even in quantities so small as to escape detection by the most accurate weighing of samples affected, permits the passage of leakage currents which heat the porcelain locally and cause the ultimate failure of the insulator by cracking or electrical puncture. It is quite generally accepted by engineers familiar with this subject that properly vitrified porcelain is not subject to depreciation; so the importance of insuring that the product of a factory is properly fired and non-porous cannot be over-estimated.

The general relationship between porosity of porcelain and firing temperature is shown in Fig. 1. From this it will be seen that it is possible to produce non-porous porcelain, provided that the ware is brought within the indicated permissible firing range and held there for a period long enough for it to reach a uniform temperature throughout, and that no part of the ware reaches a temperature above the upper limit of this range. The rate of heating and cooling is important for other reasons but does not enter into a discussion of this subject.

It is apparent, then, that the production of non-porous porcelain is a problem largely dependent on a sufficiently close control of firing. It becomes necessary, however, to have some method of simple testing that will indicate by means of properly

chosen control pieces whether the necessary degree of control is being maintained. Early in their experience in the manufacture of insulators, the Research Department of the Jeffrey-Dewitt Insulator Company was called upon to meet this demand and the result is the fuchsine method herein described.

From a consideration of the laws of physics it is evident that in a porous body in which the porosity is of the open-pore type (that is, the voids are largely connected by capillary passages, as is usually the case with porcelain), the included gases will decrease in volume as the pressure increases with constant temperature. Therefore, if such a porous body be immersed in a colored solution, the coloring particles of which

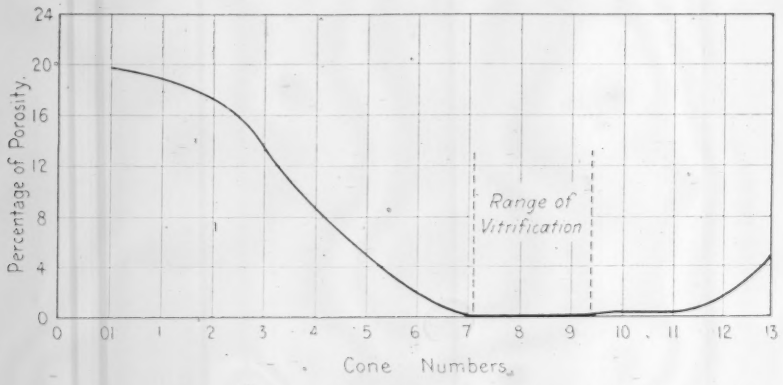


FIG. 1.—Porosity-Temperature Curve for a Typical Porcelain.

are small enough to penetrate the capillary pores, it will be possible to secure a penetration of this solution by the application of pressure. The capillary effect will assist in this action. On removal of the pressure, even if the intruded liquid is forced out again by the expanding gases, the stain will remain and thus reveal the extent of penetration when the specimen is broken.

A solution of fuchsine dye in wood alcohol has been found a cheap and efficient means for effecting this penetration and the only one really satisfactory as a penetration solution. The equipment necessary for making the test is very simple and its operation is evident from the illustration in Fig. 2. The penetration is extremely active and has been observed under

the microscope in cleavage cracks of minute quartz crystals in the porcelain. Unfortunately, this color contrast does not photograph well; so micrographs cannot be shown of this phenomenon, though it has been observed quite distinctly.

In making use of the test in the control of quantity production, test or control pieces should be secured of approximately the same volume and surface area as the pieces whose condition they are to indicate. It is therefore usually most convenient simply to use part of the ware for this purpose. From a manufacturing standpoint, this means, of course, a reduction

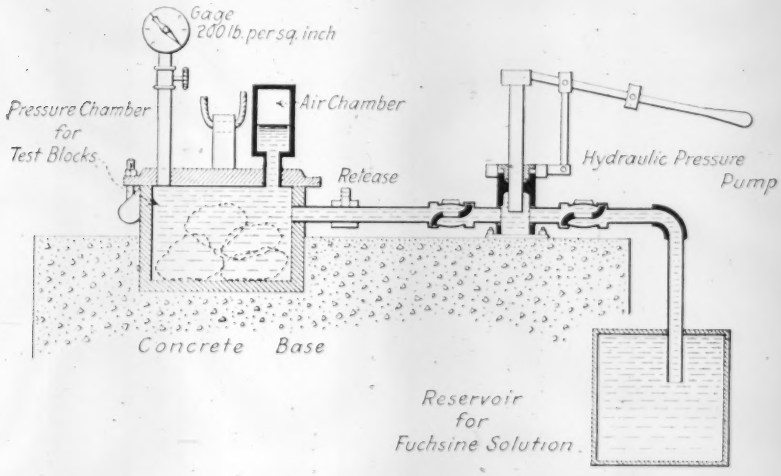


FIG. 2.—Apparatus for Fuchsine Test.

in output. The proportion of the product thus sacrificed depends to a certain extent upon the arrangement of the ware in the kiln, the kind of kiln employed, and the skill with which the kiln is operated. It should not, however, exceed two per cent of the total output.

In tunnel kiln practice one test piece per car is sufficiently representative, and the percentage destroyed in testing depends somewhat on the size of the pieces fired. In intermittent kiln practice the test pieces should be so selected as to represent as many pieces of ware as possible; yet they must be sufficiently numerous to be thoroughly representative of the entire charge.

Thus, it should be assured that all pieces represented by a given test piece will be within the permissible firing range and held within that range the required length of time, so that an acceptable test piece will indicate with reasonable certainty that the pieces it represents are likewise acceptable.

It is important that the test pieces be unglazed, in order that the penetrative action may be more rapid and reliable. Slightly defective pieces, such as those with clipped edges, may be used for test.

When the ware comes out of the kiln, the test pieces are broken up into fragments of approximately twenty-seven cubic inches in volume and placed in a vat containing the solution. A pressure of 200 lb. per sq. in. is then applied. After two hours the pressure is released and the specimens examined. The slightest measurable porosity will show a penetration of several tenths of an inch; bad porosity will show a penetration clear through a sample 2 in. thick. If a test piece shows any penetration whatever, the ware which it represents is rejected.

Laboratory experiments have been carried on with pressures up to 500 lb. per sq. in. retained for periods of days. Special experiments are being prepared to determine the effects of pressures up to 10,000 lb. per sq. in., and the effects of vacua and of extremes of heat and cold. These investigations should add greatly to our knowledge of ceramic bodies, particularly when conducted in conjunction with microscopic examinations.

When used in the usual way, the test serves two purposes. First, and most important, it insures the purchaser of porcelain a uniform and reliable product as to porosity. Second, it gives the manufacturer some idea as to the quality of raw material and the efficiency of the manufacturing process. An unusually large rejection would indicate either a change in material or an error in the process. It thus serves as a guard against carelessness in the factory that might not be detected so promptly without the test.

Used in connection with new material, the test is very convenient for determining the permissible firing range to avoid porosity. Prepared samples may be fired in small kilns at definite temperature intervals and tested for penetration. The line

is quite sharply drawn between a definitely penetrable and an absolutely impervious material.

The test has many qualifications to recommend it. It is not only simple and cheap, requiring no skilled operators, but is reliable and capable of being applied to quantity production. In fact, it is the only reliable test known to us for the detection of porosity in porcelain.

It is strongly recommended that all specifications under which porcelain for electrical purposes is purchased provide that the factory production be controlled by the fuchsine test. It will certainly insure a remarkably uniform product from a porosity standpoint, particularly if it is applied after a careful study of the kiln operation and the strategic disposition of the control pieces. A strict insistence upon such control and tests will materially improve the present situation in the electrical porcelain field.

VOLUME XX, PART II.

SUBJECT INDEX.

A

Abrasion.

The Standard Deval — Test for Rock. F. H. Jackson, 278. Discussion, 291.

Admixtures.

Effect of Hydrated Lime and Other Powdered — in Concrete. D. A. Abrams, 149. Discussion, 204.

Aggregate.

Impact Test on Concrete to Regulate Coarse and Fine — Qualities and Mixes for Highways. H. S. Mattimore, 266. Discussion, 277.

Alloying.

Molybdenum as an — Element in Structural Steels. G. W. Sargent, 5. Discussion, 29.

Alloys.

Fatigue and Impact Fatigue Tests of Aluminum —. W. A. Gibson, 115. Discussion, 133.

Alternating.

A High-Speed — Torsion Testing Machine. D. J. McAdam, 366. Discussion, 371.

Aluminum.

Fatigue and Impact Fatigue Tests of — Alloys. W. A. Gibson, 115. Discussion, 133.

Apparatus.

An — for Delicate Flexure Tests and Some Results of Such Tests. W. J. Francke, 372. Discussion, 387.

Asphalt.

The So-Called — Content of Road Oils. B. A. Anderton and D. G. Taylor, 314. Discussion, 320.

B

Brasses.

A Note on the Constitution of Certain Tin-Bearing —. William Campbell, 104.

Brinell.

A New Method for Calibrating — Hardness Testing Machines. J. L. Jones and C. H. Marshall, 392. Discussion, 396.

C

Cable.

Chain — and Some of its Physical Properties. C. G. Lutts, 80. Discussion, 102.

Calibrating.
A New Method for — Brinell Hardness Testing Machines. J. L. Jones and C. H. Marshall, 392. Discussion, 396.
Cast Iron.
Effect of Machining and of Cross-Section on the Tensile Properties of Malleable —. H. A. Schwartz, 70.
Cement.
A New Type of Automatic — Tester. T. Y. Olsen, 408.
Chain.
— Cable and Some of its Physical Properties. C. G. Lutts, 80. Discussion, 102.
Coarse Aggregate.
See **Aggregate.**
Coatings.
A New Method of Testing Galvanized —. Allerton S. Cushman, 411. Discussion, 442.
Cold-Rolling.
A Note on Stresses Caused by —. H. M. Howe and E. C. Groesbeck, 31. Discussion, 38.
Colorimeter.
A New — for White Pigments and Some Results Obtained by Its Use. A. H. Pfund, 440. Discussion, 449.
Concrete—Concretes.
Effect of Hydrated Lime and Other Powdered Admixtures in —. D. A. Abrams, 149. Discussion, 204.
Effect of Rodding —. F. E. Giesecke, 219. Discussion, 231.
Impact Test on — to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways. H. S. Mattimore, 266. Discussion, 277.
Some Determinations of the Stress-Deformation Relations for — under Repeated and Continuous Loadings. G. M. Williams, 233. Discussion, 250.

D

Deval Abrasion.
See **Abrasion.**
Ductility.
— Testing Machines. T. Y. Olsen, 398. Discussion, 404.

E

Elastic Limit.
Improved — Recorder. C. H. Marshall, 361.
Electric.
Testing of Porosity of — Porcelain. W. D. A. Peaslee, 495.

F

Fatigue.
— and Impact — Tests of Aluminum Alloys. W. A. Gibson, 115. Discussion, 133.

Fine Aggregate.
See **Aggregate.**
Fissures.
On the Shattered Zones in Certain Steel Rails, with Notes on the Interior Origin of Transverse —. J. E. Howard, 44. Discussion, 60.
Flexure.
An Apparatus for Delicate — Tests and Some Results of Such Tests. W. J. Francke, 372. Discussion, 387.

G

Galvanized.
A New Method of Testing — Coatings. Allerton S. Cushman, 411. Discussion, 422.

H

Hardness.
A New Method for Calibrating Brinell — Testing Machines. J. L. Jones and C. H. Marshall, 392. Discussion, 396.
Hiding Power.
An Instrument for Measuring the — of Paints. R. L. Hallett, 426. Discussion, 436.
High-Speed.
A — Alternating Torsion Testing Machine. D. J. McAdam, 366. Discussion, 371.
Highways.
Impact Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for —. H. S. Mattimore, 266. Discussion, 277.
Hose.
Construction of Steam —. J. M. Bierer, 355. Discussion, 359.
Hydrated Lime.
See **Lime.**

I

Impact.
Fatigue and — Fatigue Tests of Aluminum Alloys. W. A. Gibson, 115. Discussion, 133.
— Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways. H. S. Mattimore, 266. Discussion, 277.
Instrument.
An — For Measuring the Hiding Power of Paints. R. L. Hallett, 426. Discussion, 436.

L

Lime.
Effect of Hydrated — and Other Powdered Admixtures in Concrete. D. A. Abrams, 149. Discussion, 204.

M

Machining.
Effect of — and of Cross-Section on the Tensile Properties of Malleable Cast Iron. H. A. Schwartz, 70.

Malleable.
Effect of Machining and of Cross-Section on the Tensile Properties of — Cast Iron. H. A. Schwartz, 70.

Measuring.
See **Instrument.**

Molybdenum.
— as an Alloying Element in Structural Steels. G. W. Sargent, 5. Discussion, 29.

O

Oils.
The So-Called Asphalt Content of Road —. B. A. Anderton and D. G. Taylor, 314. Discussion, 320.

P

Paints.
An Instrument for Measuring the Hiding Power of —. R. L. Hallett, 426. Discussion, 436.

Petroleum.
Some Relations between the Characteristics of Steam-Distilled — Residuals. B. A. Anderton, 298. Discussion, 312.

Pigments.
A New Colorimeter for White — and Some Results Obtained by Its Use. A. H. Pfund, 440. Discussion, 449.

Plastometer.
Further Development of the — and its Practical Application to Research and Routine Problems. H. Green, 451. Discussion, 483.

Plywood.
The Uses and Properties of Water-resistant —. A. Elmendorf, 324.

Porcelain.
Testing of Porosity of Electric —. W. D. A. Peaslee, 495.

Porosity.
Testing of — of Electric Porcelain. W. D. A. Peaslee, 495.

Powdered.
Effect of Hydrated Lime and Other — Admixtures in Concrete. D. A. Abrams, 149. Discussion, 204.

R

Rails.
On the Shattered Zones in Certain Steel —, with Notes on the Interior Origin of Transverse Fissures. J. E. Howard, 44. Discussion, 60.

Recorder.
Improved Elastic Limit —. C. H. Marshall, 361.

Research.
Further Development of the Plastometer and its Practical Application to — and Routine Problems. H. Green, 451. Discussion, 483.
Residuals.
Some Relations between the Characteristics of Steam-Distilled Petroleum —. B. A. Anderton, 298. Discussion, 312.
Road Oils.
See **Oils.**
Rock.
The Standard Deval Abrasion Test for —. F. H. Jackson, 278. Discussion, 291.
Rodding.
Effect of — Concrete. F. E. Giesecke, 219. Discussion, 231.

S

Sand.
The Volume-Moisture Relation in — and a Method of Determining Surface Area Based Thereon. R. B. Young and W. D. Walcott, 137.
Shattered Zones.
On the — in Certain Steel Rails, with Notes on the Interior Origin of Transverse Fissures. J. E. Howard, 44. Discussion, 60.
Steam Hose.
See **Hose.**
Steam-Distilled Petroleum.
See **Petroleum.**
Steel—Steels.
Molybdenum as an Alloying Element in Structural —. G. W. Sargent, 5. Discussion, 29.
On the Shattered Zones in Certain — Rails, with Notes on the Interior Origin of Transverse Fissures. J. E. Howard, 44. Discussion, 60.
Stresses.
A Note on — Caused by Cold-Rolling. H. M. Howe and E. C. Groesbeck, 31. Discussion, 38.
Stress-Deformation.
Some Determinations of the — Relations for Concretes under Repeated and Continuous Loadings. G. M. Williams, 233. Discussion, 250.
Structural Steels.
See **Steels.**
Surface Area.
The Volume-Moisture Relation in Sand and a Method of Determining — Based Thereon. R. B. Young and W. D. Walcott, 137.

T

Tensile.
Effect of Machining and of Cross-Section on the — Properties of Malleable Cast Iron. H. A. Schwartz, 70.

Test—Tests.
An Apparatus for Delicate Flexure — and Some Results of Such —. W. J. Francke, 372. Discussion, 387.
Fatigue and Impact Fatigue — of Aluminum Alloys. W. A. Gibson, 115. Discussion, 133.
Impact — on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways. H. S. Mattimore, 266. Discussion, 277.
The Standard Deval Abrasion — for Rock. F. H. Jackson, 278. Discussion, 291.
Testing.
A New Method of — Galvanized Coatings. Allerton S. Cushman, 411. Discussion, 422.
—of Porosity of Electric Porcelain. W. D. A. Peaslee, 495.
Testing Machine.
A High-Speed Alternating Torsion —. D. J. McAdam, 366. Discussion, 371.
A New Method for Calibrating Brinell Hardness —. J. L. Jones and C. H. Marshall, 392. Discussion, 396.
Ductility —. T. Y. Olsen, 398. Discussion, 404.
Tester.
A New Type of Automatic Cement —. T. Y. Olsen, 408.
Tin.
A Note on the Constitution of Certain — Bearing Brasses. William Campbell, 104.
Torsion.
A High-Speed Alternating — Testing Machine. D. J. McAdam, 366. Discussion, 371.
Transverse Fissures.
See **Fissures.**

V

Volume-Moisture.
The — Relation in Sand and a Method of Determining Surface Area Based Thereon. R. B. Young and W. D. Walcott, 137.

W

Water-resistant Plywood.
See **Plywood.**

AUTHOR INDEX.

A

Abrams, D. A.
Effect of Hydrated Lime and Other Powdered Admixtures in Concrete, 149.
Discussion, 212, 231, 261.

Anderton, B. A.
Some Relations between the Characteristics of Steam-Distilled Petroleum Residuals, 298.
The So-Called Asphalt Content of Road Oils, 314.
Discussion, 312, 313, 323.

Aston, James.
Discussion, 423.

Aupperle, J. A.
Discussion, 422.

B

Beyer, A. H.
Discussion, 387.

Bierer, J. M.
Construction of Steam Hose, 355.
Discussion, 359, 360.

Bingham, E. C.
Discussion, 486, 492.

Boyd, D. K.
Discussion, 204.

Boylston, H. M.
Discussion, 396.

Burgess, G. K.
Discussion, 422.

C

Campbell, William.
A Note on the Constitution of Certain Tin-Bearing Brasses, 104.

Chamberlin, C. G.
Discussion, 404.

Clark, K. A.
Discussion, 293.

Comstock, G. F.
Discussion, 60, 134.

Cushman, Allerton S.
A New Method of Testing Galvanized Coatings, 411.
Discussion, 425.

D

Davis, M. P.
Discussion, 29.
Devries, R. P.
Discussion, 29.
Douty, D. E.
Discussion, 359.

E

Elmendorf, A.
The Uses and Properties of Water-resistant Plywood, 324.

F

Finn, A. N.
Discussion, 425.
Francke, W. J.
An Apparatus for Delicate Flexure Tests and Some Results of Such Tests, 372.
Discussion, 389.

G

Gage, R. B.
Discussion, 322.
Gardner, H. A.
Discussion, 437.
Gardner, Harry.
Discussion, 207.
Gibson, W. A.
Fatigue and Impact Fatigue Tests of Aluminum Alloys, 115.
Discussion, 135.
Giesecke, F. E.
Effect of Rodding Concrete, 219.
Discussion, 231.
Goldbeck, A. T.
Discussion, 261.
Goldmark, Henry.
Discussion, 102.
Green, H.
Further Development of the Plastometer and its Practical Application to Research and Routine Problems, 451.
Discussion, 484, 491.
Groesbeck, E. C.
A Note on Stresses Caused by Cold-Rolling, 31.

H

Hall, C. H.
Discussion, 436.
Hallett, R. L.
An Instrument for Measuring the Hiding Power of Paints, 426.
Discussion, 436, 437, 439.

Hart, L. H.
Discussion, 209.
Herschel, W. H.
Discussion, 483.
Howard, J. E.
On the Shattered Zones in Certain Steel Rails, with Notes on the Interior Origin of Transverse Fissures, 44.
Discussion, 68.
Howe, H. M.
A Note on Stresses Caused by Cold-Rolling, 31.
Discussion, 42.
Hubbard, Prévost.
Discussion, 313, 321.
Hutchinson, G. W.
Discussion, 207, 208.

J

Jackson, F. H.
The Standard Deval Abrasion Test for Rock, 278.
Job, Robert.
Discussion, 65.
Jones, J. L.
A New Method for Calibrating Brinell Hardness Testing Machines, 392.

L

Libberton, J. H.
Discussion, 277.
Lutts, C. G.
Chain Cable and Some of its Physical Properties, 80.

M

Marshall, C. H.
Improved Elastic Limit Recorder, 361.
A New Method for Calibrating Brinell Hardness Testing Machines, 392.
Mattimore, H. S.
Impact Test on Concrete to Regulate Coarse and Fine Aggregate Qualities and Mixes for Highways, 266.
Discussion, 277.
McAdam, D. J.
A High-Speed Alternating Torsion Testing Machine, 366.
Mercia, P. D.
Discussion, 133.
Moore, H. F.
Discussion, 371, 387.

O

Olsen, T. Y.
Ductility Testing Machines, 398.
A New Type of Automatic Cement Tester, 408.

P

Peaslee, W. D. A.
Testing of Porosity of Electric Porcelain, 495.
Pfund, A. H.
A New Colorimeter for White Pigments and Some Results Obtained by Its Use, 440.
Discussion, 438, 449.
Price, W. B.
Discussion, 404.

R

Rawdon, H. S.
Discussion, 61.
Rood, F. H.
Discussion, 291.

S

Sargent, G. W.
Molybdenum as an Alloying Element in Structural Steels, 5.
Discussion, 29, 30.
Schwartz, H. A.
Effect of Machining and of Cross-Section on the Tensile Properties of Malleable Cast Iron, 70.
Scoffield, H. H.
Discussion, 291.
Slater, W. A.
Discussion, 258, 261.
Smith, F. P.
Discussion, 312, 320, 322.

T

Talbot, A. N.
Discussion, 206, 231, 262, 277.
Taylor, D. G.
The So-Called Asphalt Content of Road Oils, 314.
Templin, R. L.
Discussion, 41.
Thackray, G. E.
Discussion, 425.
Thompson, G. W.
Discussion, 449, 488.

U

Upham, C. M.
Discussion, 204, 208.

V

Veitch, F. P.
Discussion, 437, 449.

W

Walcott, W. D.
The Volume-Moisture Relation in Sand and a Method of Determining Surface Area Based Thereon, 137.
Walker, Stanton.
Discussion, 250.
Webster, W. Reuben.
Discussion, 40.
White, J. A.
Discussion, 30.
Wickhorst, M. H.
Discussion, 67.
Williams, G. M.
Some Determinations of the Stress-Deformation Relations for Concretes under Repeated and Continuous Loadings, 233.
Discussion, 262.
Wilson, R. E.
Discussion, 493.
Woodward, R. W.
Discussion, 30, 38.

Y

Young, R. B.
The Volume-Moisture Relation in Sand and a Method of Determining Surface Area Based Thereon, 137.